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HAPTIC FEEDBACK IN A VIRTUAL REALITY EXERCISE GAME: DESIGN OF A STUDY AND IMPLEMENTATION OF A SYSTEM

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HAPTIC FEEDBACK IN A VIRTUAL REALITY EXERCISE GAME:
DESIGN OF A STUDY AND IMPLEMENTATION OF A SYSTEM

BY

ROBERT P. TATOIAN

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
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ABSTRACT

Exercise is an important activity which many people do not include in their lives, leading to health issues as they age. A commonly cited reason for not exercising is lack of motivation. One approach to increase motivation to exercise is to combine exercise with video games, called exergames. My research presents an experiment designed to determine how an exergame with vibrotactile feedback affects a users' intrinsic motivation, immersion, and interest in the game and a system designed for the experiment. I conducted a user study with students between the ages of 20 to 30 who played the same exergame with vibrotactile feedback for between 3 to 5 minutes and without vibrotactile feedback for between 3 to 5 minutes. The results and analysis of the data collected indicate that the system functions properly and that vibrotactile feedback can increase intrinsic motivation in an exergame user. No evidence was found that supported vibrotactile feedback increasing a user's immersion in the game. Further study is warranted due to the small sample size of the study.

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TABLE OF CONTENTS

| | |
|---|-----|
| ABSTRACT | ii |
| ACKNOWLEDGMENTS | iii |
| TABLE OF CONTENTS | iv |
| LIST OF FIGURES | vii |
| LIST OF TABLES | ix |
| CHAPTER | |
| 1 Introduction | 1 |
| 1.1 Context and Motivation of the Research | 1 |
| 1.2 What is Haptic Feedback? | 2 |
| 1.3 Outline of Thesis | 4 |
| List of References | 5 |
| 2 Background | 7 |
| 2.1 Self-Determination Theory: A Theory of Human Motivation | 7 |
| 2.2 Concepts of Immersion | 9 |
| 2.2.1 Presence | 9 |
| 2.2.2 Flow | 12 |
| 2.2.3 Levels of Immersion | 13 |
| 2.3 Commercial Systems | 14 |
| 2.4 State of the Art in Exergames | 15 |
| 2.4.1 Bicycle Systems | 16 |

| | Page |
|---|-------------|
| 2.4.2 Haptic Feedback in Exergames | 19 |
| List of References | 23 |
| 3 Design of the Experiment | 27 |
| 3.1 Design | 28 |
| 3.2 Participants | 30 |
| 3.3 Materials | 31 |
| 3.4 Procedure | 31 |
| List of References | 32 |
| 4 Experimental System | 34 |
| 4.1 Software Modules | 34 |
| 4.1.1 Serial Port Interface | 35 |
| 4.1.2 Game Controller | 35 |
| 4.1.3 The Experiment's Exergame | 40 |
| 4.2 Hardware Modules | 45 |
| 4.2.1 Front Wheel Module | 45 |
| 4.2.2 Rear Wheel Module | 46 |
| 4.2.3 Haptic Feedback Module | 48 |
| 4.2.4 Heart Rate Module | 51 |
| 4.3 Summary | 52 |
| List of References | 53 |
| 5 User Study and Data Analysis | 54 |
| 5.1 System Data | 54 |
| 5.2 Data Analysis | 56 |

| | Page |
|--|-------------|
| 5.2.1 Pre-Experiment Questionnaire | 56 |
| 5.2.2 Intrinsic Motivation and Immersion Questionnaire | 58 |
| 5.2.3 Post-Experiment Questionnaire | 64 |
| 5.3 Summary | 70 |
| List of References | 70 |
| 6 Conclusion | 72 |
| 6.1 Future Work | 73 |
| List of References | 75 |
| A Experiment Questionnaires | 76 |
| A.1 Pre-Experiment Questionnaire | 76 |
| A.2 Intrinsic Motivation Inventory - Interest/Enjoyment subscale . . | 77 |
| A.3 Immersion Questionnaire | 78 |
| A.4 Post-Experiment Questionnaire | 79 |
| A.5 Physical Activity Readiness Questionnaire | 80 |
| B Glossary | 81 |
| BIBLIOGRAPHY | 83 |

LIST OF FIGURES

| Figure | | Page |
|--------|---|------|
| 1 | The internals of an Xbox console controller. | 4 |
| 2 | The autonomy-control continuum of SDT (From: [2]). | 8 |
| 3 | An overview of communications within the application. | 34 |
| 4 | A graphical representation of the bicycle model. | 38 |
| 5 | Active and inactive collectibles in the exergame. | 40 |
| 6 | The order the participant experiences the levels of the game. . . | 42 |
| 7 | The Tutorial level | 43 |
| 8 | Tiles are selected randomly to generate a game level. | 43 |
| 9 | Generating game collectibles during game play. | 44 |
| 10 | The system's hardware modules (excluding the Heart Rate module). | 45 |
| 11 | Front Wheel module | 46 |
| 12 | An illustration of the IR sensor and blockers of the rear wheel module. | 47 |
| 13 | Haptic Feedback module | 49 |
| 14 | The two signals generated to drive the motors. | 50 |
| 15 | An example CSV file generated by the system. | 54 |
| 16 | Heart rate data recorded by the system. | 55 |
| 17 | Reported experience with video games and virtual reality. . . . | 57 |
| 18 | Intrinsic motivation scores between experiment conditions. . . . | 60 |
| 19 | Immersion scores across experiment conditions. | 62 |
| 20 | The first future use question. | 64 |

| Figure | | Page |
|---------------|--|-------------|
| 21 | The second future use question. | 65 |
| 22 | The final future use question. | 66 |
| 23 | How participants felt the virtual bicycle behaved. | 68 |

LIST OF TABLES

| Table | | Page |
|-------|---|------|
| 1 | Components of a flow state (from [9]). | 13 |
| 2 | Experiment Hypotheses | 29 |
| 3 | Levels in the game and their purpose. | 41 |
| 4 | Descriptive Statistics for the Pre-Experiment Questionnaire . . | 57 |
| 5 | Exercise frequency reported by participants. | 58 |
| 6 | Participants preference of game genres. | 58 |
| 7 | Symptoms of cybersickness reported by participants. | 69 |

CHAPTER 1

Introduction

1.1 Context and Motivation of the Research

Low physical activity is an ongoing global health issue. In 2016, nearly 28% of the world's population did not reach the level of physical activity recommended [1]. Lack of physical activity is associated with an increase in health issues such as type-2 diabetes, hypertension, and stroke [2]. In the United States the Department of Health and Human Services recommends that adults aged 18-64 perform moderate-intensity aerobic activity for 150 minutes each week, which lowers the risk of contracting these diseases [3]. However, most adults do not meet these recommendations for a variety of reasons, one of the most commonly cited reasons being a lack of motivation to exercise [4].

One approach to increase the motivation of people to exercise has been to turn video games, already considered a fun and enjoyable activity by many, into tools which can help people meet their weekly exercise requirements. Exergames, or active video games, have shown promise to increase user motivation to exercise and provide levels of physical activity comparable to traditional exercise [5, 6]. These games have seen success in the commercial market with active gaming platforms such as the Nintendo "Wii Fit" board and Microsoft Kinect device. In academic circles, exergames, both commercial and purpose-built, have been studied for a myriad of reasons such as their effects on player motivation, potential to provide an enjoyable and fun alternative to traditional exercise, and the intensity of exercise they can produce.

Recently, as low-cost head-mounted displays (HMDs) have become commercially available, virtual reality (VR) has increasingly become a popular setting for exergames. Perhaps as a result of this availability, research into making exergames

more immersive or determining what affects immersion in exergames has seen a rise in interest within the academic community [7, 8, 9, 6].

However, while these aspects have been and continue to be explored in the literature, there has been little research to date on the effects of haptic feedback in the context of exergaming. What research has been conducted has been geared towards making exergames more accessible to the handicapped.

1.2 What is Haptic Feedback?

Unlike the visual, auditory, and olfactory senses, the sense of touch is spread throughout the human body. The sense of touch enables a person to feel changes in temperature, the texture of objects, and pain among other sensations. The term “haptic” is defined as “the science of applying tactile, kinesthetic, or both sensations to human computer interactions. It refers to the ability of sensing and/or manipulating objects in a natural or synthetic environment using a haptic interface” [10]. In the field of Haptics, tactile sensations tend to be those which relate to vibration and textures, while kinesthetic sensations refer to forces and pressures. The use of tactile sensations, such as vibration, to convey information to a user is referred to as tactile feedback. Similarly, force feedback, is the use of forces to convey information. A system that can produce tactile feedback and/or force feedback is called a haptic device. In a more general sense, tactile and force feedback can be referred to under the umbrella term: haptic feedback. Haptic feedback thus is the use of tactile and/or force feedback to provide information to the user of a haptic device. Haptics can be broken into three sub-areas [10, 11]:

1. **Human haptics:** Understanding how the human sensory system responds and processes tactile and kinesthetic sensations.
2. **Machine haptics:** Building haptic devices which can be used to augment

the sense of touch through tactile or force feedback.

3. **Computer haptics:** The simulation of sensations, both tactile and kinesthetic, in a virtual environment which are presented to the user through a haptic device.

The work I discuss later in this thesis falls into the latter two areas. The haptic device I have built uses vibrational tactile haptic feedback (vibrotactile feedback) or, phrased another way, haptic feedback using vibrational tactile sensations, to alert the user when they have encountered a virtual object in a virtual environment (VE).

Examples of Devices with Haptic Feedback

Many devices exist today that use haptic feedback. The one of the most ubiquitous examples is a cell phone. Most, if not all, cell phones sold today feature a vibrotactile notification to alert a person when a call or text is received or if certain actions are triggered. On the Apple iPhone for instance, turning system settings on and off triggers a short vibration to notify the user.

Video game consoles use vibrotactile feedback to provide a rumbling sensation in game controllers. Two vibrotactile motors are typically placed in the controller handles, as in Figure 1. When a player does an action, such as shooting a gun, the game triggers the motors in the controller to emulate the feeling of recoil.

An example of a force feedback device is the Touch. The Touch is a haptic pen with six degrees-of-freedom (DOF) movement that provides three directions of force feedback [12]. It can be used for training and simulation, design, and 3D sculpting among other applications [13].



Figure 1: The internals of an Xbox console controller.

1.3 Outline of Thesis

My primary goal for this research is two-fold: To investigate the effects that haptic feedback has (1) on a users immersion in an exergame, and (2) on a users intrinsic motivation towards the exergame. To satisfy this goal I have built an exergame incorporating vibrotactile feedback and have conducted a user study to collect data regarding user performance, opinions, and attitudes towards the game.

Chapter 2 gives background information and sets the context of the thesis. The meaning of the terms intrinsic motivation and immersion are discussed and prior work on exergames is presented. Chapter 3 presents the design of experiment, formal hypotheses, population of interest, and experiment procedure. Chapter 4 discusses the construction of the system used to carry out the experiment. The system is built from a bicycle locked in a bicycle trainer and augmented to communicate with an exergame designed for the experiment. Chapter 5 discusses the data generated from testing the system and presents an analysis of the data gathered from running a user study with seven participants. To conclude this work, Chapter 6 summarizes the results of the thesis and presents possible avenues for future work.

List of References

- [1] R. Guthold, G. A. Stevens, L. M. Riley, and F. C. Bull, “Worldwide Trends in Insufficient Physical Activity From 2001 to 2016: A Pooled Analysis of 358 Population-Based Surveys with 1.9 Million Participants,” *The Lancet Global Health*, vol. 6, no. 10, pp. e1077–e1086, 2018. [Online]. Available: <https://linkinghub.elsevier.com/retrieve/pii/S2214109X18303577>
- [2] F. W. Booth, C. K. Roberts, and M. J. Laye, “Lack of Exercise Is a Major Cause of Chronic Diseases,” *Comprehensive Physiology*, vol. 2, no. 2, pp. 1143–1211, apr 2012. [Online]. Available: <http://doi.wiley.com/10.1002/cphy.c110025>
- [3] U.S. Department of Health and Human Services, “2008 Physical Activity Guidelines for Americans,” Tech. Rep., 2008. [Online]. Available: https://health.gov/paguidelines/second-edition/report/pdf/PAG_Advisory_Committee_Report.pdf
- [4] W. Ebben and L. Brudzynski, “Motivations and Barriers to Exercise Among College Students,” *Journal of Exercise Physiologyonline (JEPonline)*, vol. 11, no. 5, pp. 1–11, 2008.
- [5] M. Nunes, L. Nedel, and V. Roesler, “Motivating People to Perform Better in Exergames: Competition in Virtual Environments,” in *Proceedings 29th Annual ACM Symposium on Applied Computing - SAC '14*. Gyeongju, Republic of Korea: ACM Press, 2014, pp. 970–975. [Online]. Available: <http://dl.acm.org/citation.cfm?doid=2554850.2555009>
- [6] S. C. Barathi, E. O’Neill, C. Lutteroth, D. J. Finnegan, M. Farrow, A. Whaley, P. Heath, J. Buckley, P. W. Dowrick, B. C. Wuensche, and J. L. J. Bilzon, “Interactive Feedforward for Improving Performance and Maintaining Intrinsic Motivation in VR Exergaming,” in *Proceedings 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. Montreal QC, Canada: ACM Press, 2018. [Online]. Available: <http://dl.acm.org/citation.cfm?doid=3173574.3173982>
- [7] J. Bolton, D. Lirette, M. Lambert, and B. Unsworth, “PaperDude : A Virtual Reality Cycling Exergame,” in *Proceedings Extended Abstracts on Human Factors in Computing Systems*. Toronto, ON, Canada: ACM Press, 2014, pp. 475–478.
- [8] L. A. Shaw, B. C. Wuensche, C. Lutteroth, J. Buckley, and P. Corballis, “Evaluating Sensory Feedback for Immersion in Exergames,” in *Proceedings Australasian Computer Science Week Multiconference on - ACSW '17*. Geelong, Australia: ACM Press, 2017. [Online]. Available: <http://dl.acm.org/citation.cfm?doid=3014812.3014823>

- [9] M. Löchtefeld, A. Krüger, and H. Gellersen, “DeceptiBike: Assessing the Perception of Speed Deception in a Virtual Reality Training Bike System,” in *Proceedings 9th Nordic Conference on Human-Computer Interaction - NordiCHI '16*. New York, New York, USA: ACM Press, 2016, pp. 1–10. [Online]. Available: <http://dl.acm.org/citation.cfm?doid=2971485.2971513>
- [10] A. El Saddik, M. Orozco, M. Eid, and J. Cha, *Haptics Technologies*, 1st ed., ser. Springer Series on Touch and Haptic Systems. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011.
- [11] P. Ramsamy, A. Haffegge, R. Jamieson, and V. Alexandrov, “Using Haptics to Improve Immersion in Virtual Environments,” in *Proceedings Computational Science*. Reading, UK: Springer, Berlin, Heidelberg, 2006, pp. 603–609.
- [12] 3D Systems, “The Touch Haptic Device,” Accessed: 2019-02-18. [Online]. Available: <https://www.3dsystems.com/haptics-devices/touch>
- [13] 3D Systems, “Haptic Devices: Add the Sense of Touch to Your Digital World,” Tech. Rep., 2018. [Online]. Available: https://www.3dsystems.com/sites/default/files/2018-08/3d-systems-haptic-device-en-web-2018-08-03_0.pdf

CHAPTER 2

Background

2.1 Self-Determination Theory: A Theory of Human Motivation

Self-Determination Theory (SDT) is an empirical psychological framework concerned with the “social-contextual factors” that affect human motivation [1]. At the heart of SDT there are three “basic psychological needs” which are fundamental for human development and mental wellness: *competence*, a person’s desire to have an impact on their environment; *autonomy*, how much a person feels their behaviors or actions are controlled by themselves; and *relatedness*, a person’s need to feel like they are a part of a group and matter to other people [1]. When any of these three needs are undermined or supported they will have an affect on a person.

Within SDT, motivation is classified along an autonomy-control continuum, shown in Figure 2. Behaviours that are classified as *autonomous* within SDT are done because the person identifies them with their own beliefs; They are self-determined. On the other side of the spectrum, those activities that are described as *controlled* are not self-determined, instead they done for reasons where the person is felt pressured to engage in an action by either external or internal forces. The more autonomous a behaviour is, the more a person is willingly doing actions associated with the behaviour.

Along this continuum, motivation is broken into three types: intrinsic motivation, extrinsic motivation, and amotivation. Out of these three types, the most relevant to this thesis is intrinsic motivation. This is an autonomous type of motivation described within SDT. Behaviours that are intrinsically motivated are done because a person finds the activity enjoyable or pleasurable, regardless of an expectation or promise of rewards. In effect the activity itself is the reward [1].

Cognitive evaluation theory (CET), one of six “mini-theories” within SDT,

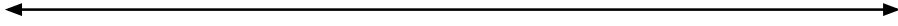
| Type of Motivation | Amotivation | Extrinsic Motivation | | | | Intrinsic Motivation |
|--|---|--|---|---|--|--|
| Type of Regulation | non-regulation | external | introjected | identified | integrated | intrinsic |
| Example Motive | <i>"I have nothing better to do with myself."</i> | <i>"because my parents are making me."</i> | <i>"I don't want to let others down by quitting."</i> | <i>"It will help open doors for my future career as a coach."</i> | <i>"it helps to confirm my identity as an athlete"</i> | <i>"I love the rush I feel when running down the field."</i> |
| Locus of Causality | impersonal | external | somewhat external | somewhat internal | internal | internal |
|  | | | | | | |
| Degree of Autonomy | non-self-determined | | | | self-determined | |

Figure 2: The autonomy-control continuum of SDT (From: [2]).

focuses solely on intrinsic motivation. Its aim is to understand and explain how a persons environment affects intrinsic motivation. CET is dedicated to examining the effect that rewards, feedback, and similar have on intrinsic motivation. Based on how a person perceives a reward, feedback, or other event for a behaviour will have an effect on their intrinsic motivation towards that behaviour by changing their perception of competence and autonomy. Rewards that are perceived as supportive of a person's autonomy and competence will reinforce their intrinsic motivation for that behaviour. On the other hand, rewards that are perceived as contingent on a specific outcome or to drive behaviour in a certain way are likely to weaken intrinsic motivation by eroding autonomy and/or competence for that behaviour.

Ryan and Deci suggest that tangible rewards, such as money, will tend to undermine intrinsic motivation [1]. While rewards that are spontaneous or provide positive verbal feedback will likely enhance feelings of competence. In most cases rewards will have multiple meanings to an individual requiring greater examination into how the reward will be perceived.

2.2 Concepts of Immersion

The term and concept of immersion with regards to video games or virtual environments does not appear to have a clear definition in the scientific literature, with several concepts being used almost interchangeably to refer to the same idea. This section presents three concepts, *presence*, *flow*, and a graded conceptualization of immersion. The last concept appears to be less prevalent in the literature than presence and flow. Section 2.2.1 presents various views on presence and immersion within the context of presence. Section 2.2.2 presents Csikszentmihalyi's flow construct. Finally, Section 2.2.3 discusses the leveled concept of immersion introduced by Brown and Cairns.

2.2.1 Presence

The concept of presence is applicable to any form of media [3]. It was defined by the International Society for Presence Research (ISPR) in 2000 as:

“a psychological state or subjective perception in which even though part or all of an individuals current experience is generated by and/or filtered through human-made technology, part or all of the individuals perception fails to accurately acknowledge the role of the technology in the experience. Except in the most extreme cases, the individual can indicate correctly that s/he is using the technology, but at *some level* and to *some degree*, her/his perceptions overlook that knowledge and objects, events, entities, and environments are perceived as if the technology was not involved in the experience. Experience is defined as a persons observation of and/or interaction with objects, entities, and/or events in her/his environment; perception, the result of perceiving, is defined as a meaningful interpretation of experience.” [4]

Phrased another way, the ISPR defines presence as a state when a person is experiencing something, a VE for instance, using a piece of technology, such as an HMD. They are aware they are using the HMD to view the VE, but they seem to “forget” that the display is there and begin to react as if the VE were real.

However, despite this definition by the ISPR there is still some debate as

to what presence is and the concept has been defined by researchers in different ways [5]. In their survey of the topic, Skarbez et al. state that presence is commonly used as “the feeling of ‘being there’ in a virtual place” [5]. They write that most definitions of the concept found in the scientific literature can be classified as either “being there” or “non-mediation,” which they state is the lack of attention to the device presenting a VE. The above definition from the ISPR falls under their category of non-meditation.

An alternative definition of presence is given by Witmer and Singer. They define presence “as the subjective experience of being in one place or environment, even when one is physically situated in another” [6]. In the same paper, they give a definition of what immersion means in the context of presence. Within presence the term immersion, in addition to the competing definitions of the concept, is sometimes used to describe the same state as presence [5]. Their definition of immersion is “a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences” [6].

Lombard and Ditton find six conceptualizations of presence in the scientific literature, one of which is presence as both perceptual and psychological immersion [3]. The ISPR again provides definitions for both concepts. They define perceptual immersion as:

“‘Spatial presence,’ ‘physical presence,’ ‘a sense of physical space,’ ‘perceptual immersion,’ ‘transportation’ and ‘a sense of being there’ occur when part or all of a persons perception fails to accurately acknowledge the role of technology that makes it appear that s/he is in a physical location and environment different from her/his actual location and environment in the physical world.” [4]

and psychological immersion as the following:

“‘Engagement,’ ‘involvement,’ and ‘psychological immersion’ occur when part or all of a persons perception is directed toward objects,

events, and/or people created by the technology, and away from objects, events, and/or people in the physical world. Note that the person's perception is not directed toward the technology itself but the objects, events and/or people the technology creates.” [4]

Continuing with a VE as an example experience the first term, perceptual immersion, relates to the technology used to create and present the VE. With this type of immersion, a person's senses ignore the technology in use and begin to perceive that the environment the technology is presenting is where they actually are. Psychological immersion, the second term, focuses on the content created by the technology and the person's awareness between the real and the virtual worlds. Awareness of surroundings shifts from the real to the virtual world, which is similar to the definition provided by Witmer and Singer.

Slater and Wilbur, however, provides an alternative definition of immersion within presence. They define immersion as an inherent part of the technology used to view a VE, based on how capable the display is of deceiving the senses [7]. This view of immersion allow two display mediums to be compared, for instance an HMD provides a more immersive experience, in this context, than a computer monitor.

Regardless of the definition of presence or immersion, it important that there is some way to measure the concept. Presence can be measured in several ways. A common method of measuring presence is through questionnaires to report “how present” someone is in a VE. Many questionnaires exist, several of which may be found in [5]. Another way to measure presence is by exposing a person to threats or social situations in a VE. The idea is that the more present someone is in a VE the more likely they will react to events in the VE as if they were real. Physiological measurements can also be used to measure presence in some way. Skin conductance, also know as galvanic skin response (GSR), and heart rate have

both been found to correlate with increased presence.

2.2.2 Flow

Flow, also called the “optimal experience,” is a mental state first described by Mihaly Csikszentmihalyi in *Beyond Boredom and Anxiety: Experiencing Flow in Work and Play* [8]. The concept arose from the author’s study of enjoyment, specifically activities which were done without the promise of reward in either the past or future (i.e. activities that are intrinsically motivated). These activities are described as “autotelic,” from the Greek words *auto* meaning self and *telos* meaning goal or purpose. Autotelic activities are therefore those which are done solely for the purpose of doing the activity. The result of performing these autotelic activities or tasks is called flow.

Flow is described as a subjective experience where a person has complete immersion in a task to the point where they lose their sense of self but retain a deep sense of control [9]. In this context immersion refers to a deep mental involvement. It is also important to note that the experience of flow will vary from person to person. There must be some form of a challenge in a task before a flow state can be entered [10]. When a person’s skill level is matched with the perceived level of the challenge encountered, flow may result. If both the level of the challenge and skill is low, apathy is said to result. On the other hand if the level of the challenge is too great and the person’s skill too low a person may experience anxiety. Finally if the person is skilled at the task and it is not very challenging the person might experience boredom or relaxation.

In Table 1 the components of the flow experience are listed. Originally, Csikszentmihalyi identified six components of flow [8]. Later an additional component, the distortion of time, was added.

Whether a person has had an experience of flow is typically measured through

Table 1: Components of a flow state (from [9]).

| |
|---|
| A merging of action and awareness. |
| Clear and unambiguous goals, accompanied by immediate feedback. |
| The centering of attention on the activity. |
| The feeling of being in control of the task or action. |
| The loss of the feeling of self-consciousness. |
| A distortion of perception of time passing. |
| The emergence of an autotelic experience. |

questionnaires. In Csikszentmihalyi's initial study flow was measured through a questionnaire and interviews with the subjects [8]. This questionnaire would later become known as the Flow Questionnaire. Another method of measuring flow includes the Experience Sampling Method. This questionnaire is given to participants at random intervals during the day. Other methods exist of measuring and classifying flow and may be found in [9].

2.2.3 Levels of Immersion

In their 2004 paper, Brown and Cairns describe three levels of immersion which they derived from interviews of seven subjects on their experiences of immersion after the subjects played their favorite video game [11]. They write that immersion is how involved a person is with a video game and describe three levels of immersion: engagement, engrossment, and total immersion. The levels follow a sequence, a person must become engaged with a game before they can become engrossed and so on. Prior to entering a specific level a person must also overcome certain barriers.

To enter the level of engagement, the player must overcome the barriers of access and investment. Here access refers to both the preferred genre of the player and the controls and feedback provided by the game. While investment deals with the time, effort and rewards, and attention involved with playing the game.

If both barriers are broken, the player may begin to become engaged with the game. After engagement a player may become engrossed. The authors state the only barrier to engrossment is the design of the game. When the game has an appealing story, visuals, and tasks this barrier is lowered and the player can become engrossed. Brown and Cairns define engrossment as “when game features combine in such a way that the gamer’s emotions are directly affected by the game” [11].

Finally the last level of immersion, total immersion, is detailed as having two barriers: empathy, feeling related to the characters in the game; and atmosphere, how relevant the game construction is to the game. After these two barriers are overcome the players may experience total immersion, which the authors state as being presence.

2.3 Commercial Systems

I would now like to turn our attention to commercial video gaming systems. Since the early 1980’s many companies have released video game controllers or systems requiring physical gestures or movements to use. The Amiga Joyboard was one of the first commercial gaming systems to incorporate the player’s body into the game they were playing. By balancing on the Joyboard the player could transform their body movements into actions in the virtual world [12]. The Power Pad controller was released in 1988 for the Nintendo Entertainment System (NES) [13]. The Power Pad was a game controller, like the Joyboard, which the player interacted with by stepping on or touching one of several buttons present on either side of the Power Pad. Both the Joyboard and Power Pad saw a limited amount of games produced specifically for the controllers [12]. In the late 1990’s an arcade game using the same style of interaction as the Power Pad was released by a game company named Konami. The game, *Dance Dance Revolution*, proved to be a hit with new releases occurring periodically since its inception. In 2006 Nintendo

released the Wii, a video game console requiring the player to use physical gestures to interact with some of the games released for the platform. Roughly two years later they released an accessory to the console called the Wii Balance Board, similar to the Joyboard. The user could stand on the device to interact with supported games.

More recently, in 2010, Microsoft released the Kinect, a camera accessory for the Xbox video game console and PC which can capture the movements of players using the accessory and translate those movements into in-game actions. In 2016 the consumer versions of the Oculus Rift and HTC Vive, two VR HMDs, were released. Initially the Oculus Rift was limited to mouse and keyboard interactions, but handheld controllers followed soon after its release. Both VR systems, as of 2019, allow players to move around a room and interact with a virtual environment through the use of tracking systems and handheld controllers.

2.4 State of the Art in Exergames

This section reviews the existing literature on exergames. As I have shown video game consoles designed for or to encourage exercise, and by extension the games that are played on them, are not a new concept. The first computer games which may be regarded as exergames appeared in the early 1980s alongside the Joyboard, with research on exergames and exergaming systems beginning around the early 2000's and continuing to today. Section 2.4.1 presents bicycle systems designed for simulation, medical purposes, and exergaming. Section 2.4.2 covers studies focused on utilizing haptic feedback in an exergame setting for either accessibility or health purposes.

2.4.1 Bicycle Systems

Some of the earliest work on exercise cycling systems include the Peloton and KAIST systems. Peloton, developed by Carraro et al. in 1998, is a system which allows users to exercise with each other through the Internet [14]. The bicycle is locked in a bicycle trainer and an attached sensor measures pedaling speed. A VE is displayed to the user via a computer monitor. To immerse its users in the VE, the system provides tactile feedback through a fan which simulates wind corresponding to the speed the user is pedaling, and by changing the resistance of the pedals in relation to the slope of the terrain [14].

The KAIST system, developed in 2001 by Kwon et al., is a more complex bicycle system than the Peloton [15]. It consists of a 6-DOF parallel hydraulic platform, speed measurement system, pedal resistance system, and handlebar system which together are capable of accurately simulating forces that may occur when riding a real bicycle. The system is integrated with a VE modeled after the Korea Advanced Institute of Science and Technology, and is displayed to the rider thorough either an HMD or a projector.

Later in 2007, Tang et al. developed a cycling simulator, which is similar to the system proposed in this thesis, intended to be used for both exercise and enjoyment [16]. Like the Peloton system the bicycle is locked in a bicycle trainer, however a frame with springs attached to the bottom allowing the bike to tilt slightly to either side during use. The system measures the angle of the front wheel and speed of the bike through a pair of encoders. It can also modify the resistance applied to the rear wheel giving the illusion of traveling on a variety of surfaces and inclines. To display the VE a pair of stereoscopic projectors are used, requiring the user to wear special glasses to view the scene [16].

The FIVIS bicycle simulator was developed by Herpers et al. in 2008 [17]. The

system is similar to the KAIST system, the bicycle is fixed to a 6-DOF parallel hydraulic platform in order to simulate realistic forces. Unlike the KAIST system, a virtual environment is displayed to the user through three large projection screens positioned to envelop their field of view.

In 2016, Lochtefeld et al. modified a commercial exercise bicycle to study the possibility of speed deception in VR with an HMD versus a speedometer [18]. To provide the user with an alternative speed when using the speedometer, they captured the measurements of a hall-effect sensor, a device commonly used in conjunction with magnets to gauge speed, initially attached to the bicycle through an Arduino board and used another to display the altered measurements. The authors also attached a standard PC fan to the training bicycle to provide tactile feedback by simulating wind blowing in a user's face.

To this point, the systems presented have focused on providing a realistic simulation or were intended as exercise platforms. The following two bicycle systems were designed for rehabilitation purposes. The final system described in this section is the system I have built for my thesis.

In 2010 Ranky et al. developed a modular rehabilitation cycling system [19]. The virtual reality augmented cycling kit (VRACK) is capable of connecting most bicycles to a computer to be used in a virtual environment. Two major components of the system are the handlebars and pedal modules. The handlebar module is a pair of stationary, 3D printed "hydraulic dynamometer[s]." Although the module is fixed, users can turn the virtual bicycle by squeezing either handlebar. The pedal modules are capable of attaching to any pedal that can be removed from a bicycle. They contain an accelerometer, hall-effect sensor, and load cell to measure the ankle motion of the user, speed, and force on both pedals, which are all used to lean the virtual bicycle to the left or the right. Since the system is intended to

be used in a rehabilitation context, it is capable of measuring the user’s heart-rate through a wireless sensor and “practitioner interface.” VRACK also incorporates haptic feedback in the form of vibrations which are triggered via events in the virtual environment [19].

The system proposed in this thesis is also similar to the rehabilitation system built by Boulanger et al. [20]. That system is intended to be a low-cost VR alternative to existing rehabilitation systems and is based around a commercial exercise training bicycle. To communicate with the sensors monitoring the patient and the state of the bicycle the authors use low-cost components such as Arduino boards and Android tablets. Since it is designed to be used in a medical context, a clinician is required to start a session alongside a patient. The patient is monitored while using the system and their data is encrypted and sent to a server located where the clinician is based.

My system is intended to be a low-cost VR bicycling system. It can be used with any bicycle that can fit in a bicycle trainer. Each module of the system communicates with the computer through an Arduino, allowing additional modules to be added or removed as needed. The system measures the bicycle speed through infrared sensors attached to the rear frame. It measures the front wheel angle through an encoder, which lets users have the freedom to turn in a VE. A heart rate sensor records data that can be saved for later analysis or used by an application. Finally, the system provides vibrotactile feedback through three vibrotactile motors attached to the handlebars and under the seat.

Summary

This section has reviewed several virtual bicycle systems found in the scientific literature in addition to mine. None of the systems found in the literature seem to be a good fit for this experiment. Both the KAIST and FIVIS systems rely

on hydraulic platforms to function properly which I do not have access to and would be too expensive to purchase. The system by Boulanger et al. is intended to be used in a clinical setting and has more overhead than is required for this experiment. The Peleton system is designed to be used with multiple players over the internet and lacks data recording. The system developed by Tang et al. is similar to mine. However, based on the results of [21], I opted not to include variable resistance in my system. Furthermore, all of the presented systems, with the exception of VRACK, lack vibrotactile feedback.

2.4.2 Haptic Feedback in Exergames

To date, there have been few studies conducted which have applied haptic feedback to exergames. Those studies that do exist can be divided into two applications: accessibility and health. This section is dedicated to presenting the existing work in both categories.

Accessibility

In this section, I present four existing studies which have investigated making exergames more accessible to the blind by applying haptic feedback. The first study, VI-Tennis, modifies a video game for the Wii game console called Wii Tennis to use tactile feedback in addition to audio [22]. This study tested the effectiveness of tactile and audio (treatment) vs audio cues alone (control) on 13 legally blind children. The results of the study showed that the subjects achieved between moderate and vigorous levels of energy expenditure (EE) with no difference in EE between the control and treatment versions of the exergame. However, subjects scored significantly better in treatment version and expressed more enjoyment towards it.

Continuing with this theme, VI-Bowling presents a modified version of another

Wii video game called Wii Bowling [22]. The modified game incorporates tactile and audio feedback again aimed at enabling the blind to participate in exergames. The modified game incorporates a novel technique which the authors term “tactile dowsing.” This technique produces increasingly stronger vibration in the Wii controller when a user points it in the correct direction, in this application, to throw the bowling ball. A user study conducted with six blind participants, playing VI-Bowling found that the game provided an EE similar to walking. Players also reported that they enjoyed the game.

Pet-N-Punch is an exergame that was developed to explore the possibility of encouraging vigorous physical activity in blind children [23]. The study examined if there was a significant difference in EE between playing with one arm vs two and used a combination of audio and tactile cues to indicate to the player what action they needed to do in the game and when to do it. The user study involving 12 blind children showed no significant difference in EE between the one-arm and two-arm conditions. However, the children showed a strong interest in playing the game.

The final work in this section presents two user studies by Morelli et al. focusing on a technique the authors call real-time sensory substitution (RTSS) [24]. RTSS allows visual cues in games to be replaced with either haptic and/or audio cues as the game is being played. Both studies used this technique in a Kinect-based exergame. In the first user study consisting of 28 adult subjects, no differences in performance between the traditionally played Kinect exergame (control) and the exergame using RTSS (treatment) was found. The second user study tested RTSS on seven blind adults and found no difference in performance between the two groups. These results led the authors to conclude that RTSS can be used to augment games involving bodily interaction, potentially expanding the

range of games the blind can play.

Health

Stach and Graham conducted three studies using separate games which incorporated either kinesthetic or tactile feedback to study if haptic feedback can balance gameplay between two unequal players, prevent players from overexerting themselves, and enhance the feeling of presence [25]. In the first game, Truck Pull, players would compete against each other on exercise bikes in a tug-of-war. Balloon Burst, the second game, encouraged players to compete with each other by shooting as many balloons as possible while pedaling on a stationary bicycle. To shoot the balloons players used a controller that vibrated when a balloon was hit. The third game, Pedal Race, consisted of a 2D racetrack that two players would race around by pedaling on a recumbent exercise bike. This game varies the resistance of the pedals to provide the players kinesthetic feedback.

They found that the two exergames using kinesthetic feedback, Truck Pull and Pedal Race, improved the users sense of presence and enjoyment. The second exergame with tactile feedback did not show such an improvement. This was attributed towards the manner in which the feedback was presented and that participants found it challenging to interpret the meaning of the vibrations. The authors suggest that haptic feedback should have a clear link to physical actions in the game and that kinesthetic feedback should not frustrate the player.

M. Hossain et al. present an exergame framework centered around tactile feedback for obesity treatment [26]. The framework has several modules to monitor users and their interactions with a game. To evaluate the framework the authors developed an exergame and tested it on 12 obese participants between the ages of 8 to 45. To find clues, which provide vibrotactile feedback when found, the game requires players to perform an exercise. The participants found the game

entertaining and had a level of physical activity comparable to walking or running.

Motivated to encourage seniors to exercise, Alizadeh et al. present a prototype of a system intended to encourage group exercise among the elderly [27]. The prototype allows for one leader and one follower. A Kinect is used to determine the follower's motions. Three different waveforms of vibrotactile feedback are used in the system: "constant push/pull," "corrective feedback," and "notification metaphor." These waveforms are played to keep the follower in sync with the leader. The authors conducted a preliminary study of five adults. Without prior explanation participants found the vibrations confusing; although the constant push/pull notification seemed to reduce confusion. They also felt uncomfortable or would become numb to the feedback with longer vibrations. The authors suggest that for some, vibrations require an explanation to be meaningful and that they should not last longer than five seconds.

Hung et al. present a prototype or hypothetical wearable system intended to investigate the effects of kinesthetic feedback in exergames [28].

To determine what types of sensory feedback motivate and immerse exergame players the most Shaw et al. examined three types of feedback: audio, tactile feedback using wind, and resistance feedback [21]. They found that all three types of feedback increased intrinsic motivation and immersion. However resistance feedback did not provide as great of an increase as the other types. They conclude that variable resistance can be neglected in an exergame and still provide immersive and motivating gameplay.

Summary

We have reviewed several exergame papers using haptic feedback for either accessibility or general health purposes. To date there is little work done in examining the psychological effects of haptic feedback in exergames, something noted in

a systematic review of exergaming literature by Lee et al. [29]. In general, much of the exergaming literature that has applied haptic feedback has focused on seeing if vibrotactile feedback can be used to affect energy expenditure or how to use it appropriately. I draw two observations based on the available work in the area. The first observation is from [25, 27] that tactile feedback needs to be used in a way that has a concrete meaning to avoid confusing the user. Second, according to [27], the duration of the vibrotactile feedback should be kept short in order to be felt.

List of References

- [1] R. M. Ryan and E. L. Deci, *Self-Determination Theory: Basic Psychological Needs in Motivation, Development, and Wellness*, 1st ed. New York, NY, USA: The Guilford Press, 2017.
- [2] M. R. Weiss and A. J. Amorose, "Motivational Orientation and Sport Behavior," in *Advances in Sport Psychology*, 3rd ed., T. S. Horn, Ed. Champaign, IL: Human Kinetics, 2008, p. 133.
- [3] M. Lombard and T. Ditton, "At the Heart of It All: The Concept of Presence," *Journal of Computer-Mediated Communication*, vol. 3, no. 2, pp. 0–0, jun 2006. [Online]. Available: <https://academic.oup.com/jcmc/article/4080403>
- [4] International Society for Presence Research, "The Concept of Presence: Explication Statement," 2000, Accessed: 2019-02-18. [Online]. Available: <https://ispr.info/about-presence-2/about-presence/>
- [5] R. Skarbez, F. P. Brooks, Jr., and M. C. Whitton, "A Survey of Presence and Related Concepts," *ACM Computing Surveys*, vol. 50, no. 6, pp. 1–39, 2017.
- [6] B. Witmer and M. Singer, "Measuring Presence in Virtual Environments: A Presence Questionnaire," *Presence*, vol. 7, no. 3, pp. 225–240, 1998.
- [7] M. Slater and S. Wilbur, "A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments," *Presence*, vol. 6, no. 6, pp. 603–616, 1997. [Online]. Available: <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.472.622&rep=rep1&type=pdf>
- [8] M. Csikszentmihalyi, *Beyond Boredom and Anxiety: Experiencing Flow in Work and Play*. San Fransisco, CA, USA: Jossey-Bass Publishers, 1975.

- [9] S. Engeser, M. S. Ganesh, G. B. Moneta, C. Pfeifer, and C. Peifer, "Advances in Flow Research," in *Advances in Flow Research*, S. Engeser, Ed. New York, NY: Springer New York, 2012, ch. 1, p. 231. [Online]. Available: <http://www.springerlink.com/index/10.1007/978-1-4614-2359-1>{%}0A<http://link.springer.com/10.1007/978-1-4614-2359-1><http://link.springer.com/10.1007/978-1-4614-2359-1>
- [10] S. A. Jackson, "Flow," in *The Oxford Handbook of Human Motivation*, 1st ed., P. E. Nathan and R. M. Ryan, Eds. New York, NY, U.S.A.: Oxford University Press, Inc., 2012, ch. 8, pp. 127–140.
- [11] E. Brown and P. Cairns, "A Grounded Investigation of Game Immersion," in *Proceedings Extended Abstracts of the 2004 Conference on Human Factors and Computing Systems*. Vienna, Austria: ACM Press, 2004, pp. 1297–1300.
- [12] I. Bogost, "The Rhetoric of Exergaming," Georgia Institute of Technology, Atlanta, GA, Tech. Rep., 2005. [Online]. Available: http://bogost.com/writing/the_rhetoric_of_exergaming/
- [13] K. Orland and C. Remo, "Games For Health: Noah Falstein On Exergaming History," 2008, Accessed: 2018-10-27. [Online]. Available: http://www.gamasutra.com/view/news/109512/Games_For_Health_Noah_Falstein_On_Exergaming_History.php
- [14] G. U. Carraro, M. Cortes, J. T. Edmark, and J. R. Ensor, "The Peloton Bicycling Simulator," in *Proceedings Third Symposium on Virtual Reality Modeling Language*. Monterey, CA, USA: ACM Press, 1998, pp. 63–70. [Online]. Available: <http://portal.acm.org/citation.cfm?doid=271897.274372>
- [15] D.-S. Kwon, G.-H. Yang, C.-W. Lee, J.-C. Shin, Y. Park, B. Jung, D. Y. Lee, K. Lee, S.-H. Han, B.-H. Yoo, K.-Y. Wohn, and J.-H. Ahn, "KAIST Interactive Bicycle Simulator," in *Proceedings 2001 ICRA. IEEE International Conference on Robotics and Automation*, vol. 3. Seoul, South Korea: IEEE, 2001, pp. 2313–2318. [Online]. Available: <http://ieeexplore.ieee.org/document/932967/>
- [16] Y.-M. Tang, M. H.-C. Tsoi, D. T.-P. Fong, P. P.-Y. Lui, K.-C. Hui, and K.-M. Chan, "The Development of a Virtual Cycling Simulator," in *Proceedings Second International Conference on Edutainment*. Hong Kong, China: Springer, Berlin, Heidelberg, 2007, pp. 162–170. [Online]. Available: https://doi.org/10.1007/978-3-540-73011-8_18https://doi.org/10.1007/978-3-540-73011-8_18
- [17] R. Herpers, W. Heiden, M. Kutz, D. Scherfgen, U. Hartmann, J. Bongartz, and O. Schulzyk, "FIVIS Bicycle Simulator," in *Proceedings 2008 Conference on Future Play Research, Play, Share - Future Play '08*. Toronto,

- Ontario, Canada: ACM Press, 2008, pp. 244–247. [Online]. Available: <http://portal.acm.org/citation.cfm?doid=1496984.1497035>
- [18] M. Löchtefeld, A. Krüger, and H. Gellersen, “DeceptiBike: Assessing the Perception of Speed Deception in a Virtual Reality Training Bike System,” in *Proceedings 9th Nordic Conference on Human-Computer Interaction - NordiCHI '16*. New York, New York, USA: ACM Press, 2016, pp. 1–10. [Online]. Available: <http://dl.acm.org/citation.cfm?doid=2971485.2971513>
 - [19] R. Ranky, M. Sivak, J. Lewis, V. Gade, J. E. Deutsch, and C. Mavroidis, “VRACK - Virtual Reality Augmented Cycling Kit: Design and Validation,” in *Proceedings 2010 IEEE Virtual Reality Conference (VR)*. Waltham, MA, USA: IEEE, mar 2010, pp. 135–138. [Online]. Available: <http://ieeexplore.ieee.org/document/5444798/>
 - [20] P. Boulanger, A. Pournajib, W. Mott, and S. Schaeffer, “A Low-Cost Virtual Reality Bike for Remote Cardiac Rehabilitation,” in *Proceedings EuroVR*, Laval, France, 2017, pp. 155–166. [Online]. Available: http://link.springer.com/10.1007/978-3-319-72323-5_10
 - [21] L. A. Shaw, B. C. Wuensche, C. Lutteroth, J. Buckley, and P. Corballis, “Evaluating Sensory Feedback for Immersion in Exergames,” in *Proceedings Australasian Computer Science Week Multiconference on - ACSW '17*. Geelong, Australia: ACM Press, 2017. [Online]. Available: <http://dl.acm.org/citation.cfm?doid=3014812.3014823>
 - [22] T. Morelli, J. Foley, and E. Folmer, “VI-Bowling: A Tactile Spatial Exergame for Individuals with Visual Impairments,” in *Proceedings 12th International ACM SIGACCESS Conference on Computers and Accessibility*. Orlando, Florida, USA: ACM Press, 2010, pp. 179–186. [Online]. Available: <https://dl.acm.org/citation.cfm?id=1878836>
 - [23] T. Morelli, J. Foley, L. Lieberman, and E. Folmer, “Pet-N-Punch: Upper Body Tactile/Audio Exergame to Engage Children with Visual Impairments into Physical Activity,” in *Proceedings Graphics Interface Conference*. St. John’s, Newfoundland, Canada: Canadian Human-Computer Communications Society School of Computer Science, 2011, pp. 223–230.
 - [24] T. Morelli and E. Folmer, “Real-time Sensory Substitution to Enable Players Who are Blind to Play Video Games Using Whole Body Gestures,” *Entertainment Computing*, vol. 5, no. 1, pp. 83–90, 2014.
 - [25] T. Stach and T. C. N. Graham, “Exploring Haptic Feedback in Exergames,” in *Proceedings INTERACT 2011*, P. Campos, N. Graham, J. Jorge, N. Nunes, P. Palanque, and M. Winckler, Eds., vol. 6947. Springer, Berlin, Heidelberg, 2011, pp. 18–35. [Online]. Available: http://link.springer.com/10.1007/978-3-642-23771-3_2

- [26] M. S. Hossain, M. M. Hassan, and A. Alamri, “An Exergame Framework for Obesity Monitoring and Management,” in *Proceedings HAVE 2013 - 2013 IEEE International Symposium on Haptic Audio-Visual Environments and Games*, Istanbul, Turkey, 2013.
- [27] H. Alizadeh, R. Tang, E. Sharlin, and A. Tang, “Haptics in Remote Collaborative Exercise Systems for Seniors,” in *Proceedings Extended Abstracts on Human Factors in Computing Systems*. Toronto, ON, Canada: ACM Press, 2014, pp. 2401–2406. [Online]. Available: <http://dx.doi.org/10.1145/2559206.258131>
- [28] K. Hung, N. Wan, S. O. Choy, C. Chu, and D. H. Chow, “Design of an Exergaming System with Haptic Feedback for the Investigation of Energy Expenditure and Muscle Activities,” in *IEEE International Conference on Industrial Informatics (INDIN)*, Emden, Germany, 2017, pp. 886–889.
- [29] S. Lee, W. Kim, T. Park, and W. Peng, “The Psychological Effects of Playing Exergames: A Systematic Review,” *Cyberpsychology, Behavior, and Social Networking*, vol. 20, no. 9, sep 2017. [Online]. Available: <http://online.liebertpub.com/doi/10.1089/cyber.2017.0183>

CHAPTER 3

Design of the Experiment

In this chapter I present the design of the experiment, description of participants and criteria for participation, description of the materials used, and experiment procedure. The questions this experiment was designed to answer is: **Will adding tactile vibrotactile feedback to an exercise game lead to the user reporting a higher level of intrinsic motivation or immersion after playing the game? Additionally, as a result, will there be greater physiological outcomes and higher user interest in continuing to use the game containing vibrotactile feedback?**

The experiment, as I will discuss later, has two conditions: an exergame with vibrotactile feedback and the same game without vibrotactile feedback. In the exergame participants pedal forward along a road trying to gather collectibles. In the first condition when a participant rides over a collectible in the virtual environment a sound is played and vibrotactile feedback is produced letting them know they have picked one up.

My belief is that vibrotactile feedback will support a user's feeling of competence (Section 2.1) when playing the game, reinforcing their intrinsic motivation for playing the game. I also expect a higher level of immersion to be reported as the vibrotactile feedback provides (1) a way for player to know if they are playing the game correctly and (2) a reward for doing what the game designer intended. In the context of [1] players should experience the level of immersion called "engagement."

3.1 Design

The experiment has one factor, vibrotactile feedback, with two levels: vibrotactile feedback and no vibrotactile feedback. The treatment is the presence or absence of vibrotactile feedback in an exergame. The primary endpoints are the user’s motivation, immersion, and heart-rate. Table 2 shows the formal hypotheses for the study.

The independent variable is controlled by treatment randomization. Randomization is done to remove bias in treatment assignment from the participant, who might experience the novelty effect, and investigator, who may unknowingly assign only certain groups of people to a condition. To do the randomization, a pseudo-random number generator assigns the participant’s starting condition to either the vibrotactile feedback or no vibrotactile feedback condition.

A person’s feelings of motivation and immersion are subjective, therefore they are reported through the use of surveys. Four surveys are used to collect demographic information about the participants, measure the dependent variables, and answer questions regarding future use of the system. The survey questions can be found in Appendix A.

To measure intrinsic motivation the interest/enjoyment subscale of the Intrinsic Motivation Inventory (IMI) was chosen, due to prior usage in the literature as “the self-report[ed] measure of intrinsic motivation” [2]. The interest/enjoyment sub-scale is commonly used to measure a subject’s intrinsic motivation related to some task or experience, throughout the thesis I will refer to the interest/enjoyment subscale as the intrinsic motivation questionnaire. To measure participant immersion, I developed a shorter version of the questionnaire in [3] as the full questionnaire would be too long to ask during the experiment. Finally, the questions aimed at understanding which system participants would prefer to use in the future and

Table 2: Experiment Hypotheses

H_0 : There is no difference in a user’s intrinsic motivation towards the exergame when playing with vibrotactile feedback present versus without vibrotactile feedback.

H_1 : A user’s reported intrinsic motivation towards the exergame is greater when playing with vibrotactile feedback present versus without vibrotactile feedback.

H_0 : There is no difference in a user’s reported immersion in the exergame when playing with vibrotactile feedback present versus without vibrotactile feedback.

H_1 : A user’s reported intrinsic motivation towards the exergame is greater when playing with vibrotactile feedback present versus without vibrotactile feedback.

H_0 : There is no difference in a user’s heart rate in the exergame when playing with vibrotactile feedback present versus without vibrotactile feedback.

H_1 : A user’s reported intrinsic motivation towards the exergame is greater when playing with vibrotactile feedback present versus without vibrotactile feedback.

if they felt the vibrotactile version would increase their exercise frequency were inspired by some of the questions asked in [4].

To compute an intrinsic motivation score from the intrinsic motivation questionnaire the designers say the scores for Questions 3 and 4 (Appendix A.2) should be reverse scored and all the scores for the sub-scale should be averaged together. The score a participant can give for each question on the intrinsic motivation questionnaire is on a closed interval 0 to 100. To reverse score both questions the score

the participant gives is subtracted from 100 and the result is used as the score for the respective question.

The immersion questionnaire (Appendix A.3) has six questions. Questions 1, 2, 5, and 6 are intended to capture how immersed a person felt in the exergame and are averaged together to calculate an immersion score. Question 3 measures how much the participant would like to continue playing the game. Finally, Question 4 is intended to indicate if the feeling of immersion is related to the collectibles.

3.2 Participants

The target population of interest is all healthy adults between the ages of 18-64. Participants for the experiment are drawn from the University of Rhode Island's student and faculty body. Those who are pregnant are excluded from participating. According to IRB policy, research studies where subjects participate in exercise must include a health screening of each participant [5]. Whether a subject is healthy is determined by administering a Physical Activity Readiness Questionnaire (PAR-Q). The PAR-Q (Appendix A.5) is a medical questionnaire used to gauge if a subject should participate in research involving physical exertion.

In addition to the PAR-Q, blood pressure measurements are taken to further determine a participant's health. A measurement of less than or equal to 120 mmHg systolic¹ and less than or equal to 80mmHg diastolic² is considered normal blood pressure [7]. Participants for whom higher values are recorded may have hypertension and could be placed at greater than normal risk by participating in exercise. All values lower than 120/80 were eligible for participation. Participants who have readings higher than 120/80 are told they are ineligible to participate in the study. The participant's pulse is measured to detect any abnormalities. To be considered for participation, the resting pulse must be between 60 and 100 beats

¹The systolic pressure refers to the pressure in the blood vessels during a heart beat [6].

²The diastolic pressure refers to the pressure in the blood vessels between heart beats [6].

per minute (bpm) [8].

3.3 Materials

The experiment is run on a computer with an Intel i5-6500 3.2 GHz CPU, 16 GB of RAM, and an NVIDIA GeForce 1070 GTX graphics card. An Oculus Rift CV1 HMD is used to display the virtual environment to the participant. Unity 2018.2 is used to create the virtual environments and gameplay. A regular road bicycle was augmented with several Arduino-driven sensors to measure the speed the user is pedaling and the direction they are turning the front wheel.

3.4 Procedure

The investigator first reads a script to the participant that explains the experiment and gives instructions for the exergame. The instructions tell the participant they can request to discontinue the experiment at any point. They also let participants know that they only need to play the game for three minutes; although if they want to they can play for another two minutes. After the investigator finishes reading the script the participant is given three minutes to read the experiment consent form and decide if they wished to continue to participate in the study.

If the participant gives consent, they are given the PAR-Q to fill out and the investigator measures their vitals. If the participant passes the health screening, they are given the pre-experiment questionnaire (Appendix A.1) asking demographic questions, their history with virtual reality, haptic feedback, exercise frequency, and prior experience with playing video games. After finishing the survey the participant attaches the heart-rate monitor to their arm, gets on the bicycle, and puts on the HMD.

Once set up on the bicycle, the participant reads instructions in the virtual environment and plays a tutorial level. This level is intended to familiarize them

with the controls for the bicycle by having them navigate through three waypoints. After finishing this level they are given a five minute break, where they can walk around.

Following the break, the participant plays one of the two treatments, depending on which one they were initially randomized to. Regardless of the condition, the participant must collect virtual objects in the exergame while riding the bicycle. In the vibrotactile feedback condition the virtual objects, when collided with, will trigger a pulsing vibration from motors contained inside the handlebars of the bicycle and underneath the seat. In the non-vibrotactile feedback condition they do not. After three minutes a screen pops up in the VE allowing the participant to continue for another two minutes or quit the condition.

After finishing the first condition, the participant takes another five-minute break and fills out the survey questions in Appendices A.2 and A.3. The wording of the questions varies slightly for the intrinsic motivation questionnaire depending on which condition was just experienced. At the end of the break they begin the other condition they have not experienced. Once that condition is finished, they fill out the same survey questions (Appendices A.2 and A.3), with the wording depending on what condition they were just in. Finally the participant fills out the post-experiment questionnaire (Appendix A.4) and is told that the experiment is finished.

List of References

- [1] E. Brown and P. Cairns, “A Grounded Investigation of Game Immersion,” in *Proceedings Extended Abstracts of the 2004 Conference on Human Factors and Computing Systems*. Vienna, Austria: ACM Press, 2004, pp. 1297–1300.
- [2] std: Self-Determination Theory, “Intrinsic Motivation Inventory (IMI) Scale,” Accessed: 2018-09-14. [Online]. Available: <http://selfdeterminationtheory.org/intrinsic-motivation-inventory/>

- [3] C. Jennett, A. L. Cox, P. Cairns, S. Dhoparee, A. Epps, T. Tijs, and A. Walton, "Measuring and Defining the Experience of Immersion in Games," *International Journal of Human-Computer Studies*, vol. 66, no. 9, pp. 641–661, sep 2008. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S1071581908000499>
- [4] L. A. Shaw, B. C. Wunsche, C. Lutteroth, S. Marks, J. Buckley, and P. Corballis, "Development and Evaluation of an Exercycle Game Using Immersive Technologies," in *Proceedings 8th Australasian Workshop on Health Informatics and Knowledge Management (HIKM 2015)*, A. Maeder and J. Warren, Eds., vol. 164, no. January. Parramatta, Australia: CRPIT, 2015, pp. 27–30. [Online]. Available: <https://www.cs.auckland.ac.nz/~lutteroth/publications/ShawEtAl2015-ImmersiveExercycle.pdf>
- [5] University of Rhode Island Office of Research Integrity, "Exercise Policy," Kingston, RI, pp. 1–2. [Online]. Available: <https://www.irbnet.org/release/export/download.jsp?libId=21947>
- [6] Centers for Disease Control and Prevention, "Measuring Blood Pressure," 2018, Accessed: 2019-01-08. [Online]. Available: <https://www.cdc.gov/bloodpressure/measure.htm>
- [7] Centers for Disease Control and Prevention, "High Blood Pressure Fact Sheet," 2016, Accessed: 2017-12-17. [Online]. Available: https://www.cdc.gov/dhdsr/data_statistics/fact_sheets/fs_bloodpressure.htm
- [8] American Heart Association, "All About Heart Rate (Pulse)," Accessed: 2018-09-17. [Online]. Available: <http://www.heart.org/en/health-topics/high-blood-pressure/the-facts-about-high-blood-pressure/all-about-heart-rate-pulse>

CHAPTER 4

Experimental System

To conduct the study described previously in Chapter 3, an exergame and bicycle meeting the needs of the experiment had to be constructed. I used Unity¹, a software program for video game development, to build the game and software portion of the system. To construct the hardware side, I used several Arduino boards and components I sourced from different hardware vendors. This chapter is split into two sections. Section 4.1 is dedicated to the software developed for the system and the game used in the experiment, and Section 4.2 discusses the hardware used in augmenting a bicycle for the experiment.

4.1 Software Modules

The software written for the system can be divided into three modules: the Serial Port Interface, the Game Controller, and the Exergame, as shown in Figure 3. While they all are part of the same application, they each have separate purposes. The Serial Port Interface is described in Section 4.1.1 and manages the communications between the Game Controller and the various hardware modules presented in Section 4.2.

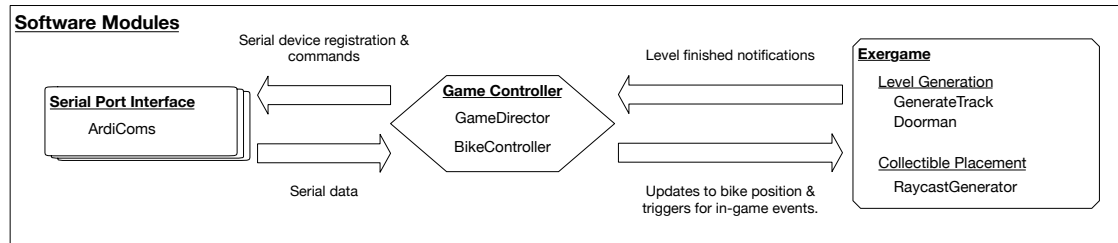


Figure 3: An overview of communications within the application.

The Game Controller, which is described in Section 4.1.2, is responsible for

¹<https://unity3d.com>

querying or controlling the hardware modules mentioned above. The user does not knowingly interact with the controller software. The last module, which is referred to as the Exergame, described in Section 4.1.3, comprises all the code which is related to the exergame the user plays.

4.1.1 Serial Port Interface

The Serial Port Interface (SI) is a wrapper around several functions in the .NET “SerialPort” class. This module provides a layer of abstraction between the serial port objects and the Game Controller modules (Section 4.1.2), and provides some error handling if the port cannot be open or created. An added benefit is that if the .NET developers change the “SerialPort” class API in the future, the SI keeps any updates that would need to be made to my code contained to a single module.

Internally, the SI maintains a list of serial port objects that are opened. This list persists for the lifetime of the program. When a serial port object is first created by a call to the SI, the baud rate, COM port, and device name are passed to an initialization function. If the port can be created, it returns a struct data type containing the index of the port in the list. This index can be stored and used by the calling program to send data to the serial device or close the serial port and remove it from the internal list. When a program uses the SI to send data to a registered serial device, the SI by default has a read timeout of 4 ms. If data is available from the serial device it will be read immediately after the data is sent to the device.

4.1.2 Game Controller

The Game Controller module includes the *Game Director* and *Bike Controller* scripts. The Game Director manages both the experiment and some communica-

tion between the game and the SI. The Bike Controller updates the position of the bicycle within the game according to the bicycle model and data received from the SI.

Game Director

The Game Director is a Unity asset (game object) created to manage the overall logic of the experiment. Only one instance of the Game Director can persist across the entire experiment. On beginning an experiment session, the Game Director determines what the Participant ID number is. The Participant ID is a pseudo-random number created so that data generated by the system can be linked with the responses a participant gives to the survey questions (Appendix A). The Game Director also uses the same pseudo-random number generator to determine what experiment condition the participant begins in.

Shortly after generating the Participant ID the Game Director communicates with the SI to initialize the attached serial devices. The serial devices to connect to are specified in a configuration file which has the COM port name, the baud rate², and a name for the device. If any of the devices cannot be connected to, the application will quit and log an error. Otherwise, a reference to the initialized serial device is stored by the Game Director in a list containing the opened serial port, device name, and baud rate.

Throughout the rest of the experiment, the Game Director handles events from the user interface and raises events in the game. Events from the user interface are button clicks which trigger level transitions, such as transitioning from a Wait Screen level to an Experiment Condition level, discussed in Section 4.1.3. When an Experiment Condition level is started, the Game Director will set and start a three-minute timer. Once this time elapses, a screen will be triggered in the

²The frequency of communication between two devices.

game to give the player an option to either continue or end the current experiment condition. If the player chooses to continue the current condition, a second timer is set and the condition will continue until two minutes have passed. In both cases, after either three or five minutes, the Game Director will prompt the player to leave the current experiment condition and transition them to a Wait Screen level for a five minute cooldown.

The last responsibility of the Game Director is to control when the Haptic Feedback module is triggered and to update the heart-rate module with the current level name. When a game level is changed, the Game Director sends to the heart rate module the name of the level and whether or not the Haptic Feedback module is enabled.

Bike Controller

The Bike Controller drives the motion of the virtual bicycle in the VE by taking the data received from the serial devices connected to the bicycle and applying it to a model (Figure 4). The bicycle model is a dynamic system. A dynamic system is described by both a state vector and a state equation. The state vector describes all the terms needed to model the system. The state vector of the bicycle system, s , is defined in Equation (1). The variables x and z are the coordinates of the center of the rear wheel in the VE. The speed of the bicycle is denoted v . The heading angle of the bicycle, θ , is relative to the VE's global coordinate system. Finally the instantaneous curvature, κ (Equation (3)), is the inverse of the instantaneous radius of curvature in Equation (2). In both Equations (2) and (3) the term L refers to the distance between the two axles of the bicycle. φ represents the angle of the front wheel of the bicycle with reference to the bicycle frame. When φ and κ are 0 the bicycle moves in a straight line. The term a is the instantaneous acceleration of the bicycle. Equation (5) is the state equation which, gives the time

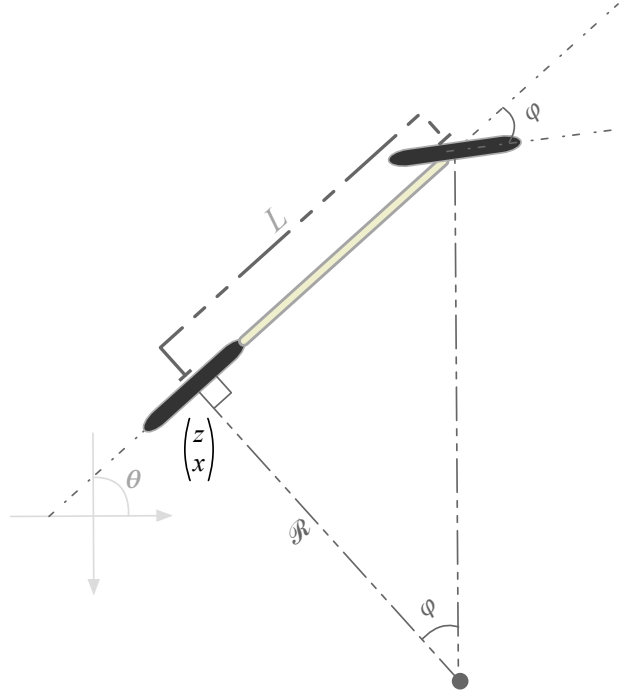


Figure 4: A graphical representation of the bicycle model.

derivatives of the components of the state vector.

$$s = \begin{bmatrix} x \\ z \\ \theta \\ v \\ \kappa \end{bmatrix}, \quad (1)$$

$$\mathcal{R} = \frac{L}{\tan \varphi}, \quad (2)$$

$$\kappa = \frac{1}{\mathcal{R}} = \frac{\tan \varphi}{L}, \quad (3)$$

$$c = \begin{bmatrix} \varphi \\ a \end{bmatrix}. \quad (4)$$

The state equation describes how the state vector changes over time. It is as a first order differential equation of the form:

$$\dot{s} = f(s, c, t),$$

where c is a control vector (Equation (4)) that groups all the controls that can be applied to the system.

$$\dot{s} = \begin{bmatrix} \dot{x} \\ \dot{z} \\ \dot{\theta} \\ \dot{v} \\ \dot{\kappa} \end{bmatrix} = \begin{bmatrix} v \cos \theta \\ v \sin \theta \\ v \kappa \\ a \\ \frac{(1 + \tan^2 \varphi) \dot{\varphi}}{L} \end{bmatrix}. \quad (5)$$

The state vector used in the exergame is a simplified version of what was just discussed. In this case, since the system cannot measure the acceleration force the user applies to the bicycle and the angle φ is given to us we cannot use the general model. In the exergame the state vector, shown in Equation (6), is a 3 by 1 vector with only the z , x , and θ terms remaining. The speed, v , is directly calculated from sensor measurements and since κ is calculated from φ and L , which are either known or measured directly through sensors, it can be removed from the state vector. The position of the virtual bicycle is updated over time by performing Euler integration on the simplified state vector in Equation (7). The use of a simple Euler integration technique, as opposed to the RungeKutta family of methods, is common in systems that involve a human in the control loop. Since a person is controlling the virtual bicycle they will correct for errors resulting from the integration.

$$s = \begin{bmatrix} x \\ z \\ \theta \end{bmatrix}, \quad (6)$$

$$\dot{s} = \begin{bmatrix} \dot{x} \\ \dot{z} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} v \cos \theta \\ v \sin \theta \\ v \kappa \end{bmatrix}. \quad (7)$$

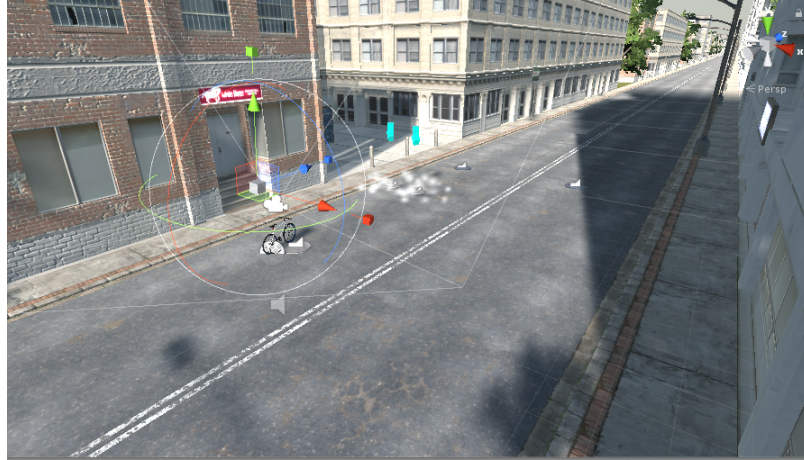


Figure 5: Active and inactive collectibles in the exergame.

4.1.3 The Experiment's Exergame

The gameplay objective of the exergame is to pick up collectibles, depicted as manholes, while pedaling as far as possible along a straight, endless road. A collectible can be either active or inactive (Figure 5), as described later in this section. Active collectibles will have a blue arrow bobbing over them indicating that they can be picked up. The arrow was added after early testers found it difficult to constantly look at the ground to find the collectibles.

The game takes place in a city environment, designed for this experiment. A city was chosen because there was some concern that participants might feel discomfort if the ground they were biking over did not appear flat, since the system cannot simulate changes in incline for the participant. The participant has three minutes to play the game but, as stated in Chapter 3, may take up to five minutes total to play.

There are two different versions of the game. For both versions, the levels are structured identically. There is a straight road along which collectibles are placed as the game is played. The difference between the two levels is that the collectibles in the vibrotactile experiment condition of the exergame will trigger

motors attached to the bicycle. To avoid biasing the participants' response to the survey questions which are presented after each condition, we do not display their score to them.

This style of game was chosen because of its simplicity and ease of implementation. Participants were expected to easily understand the task they were being asked to complete, even if they had no prior experience with video games or virtual reality. In addition to simplicity and ease of implementation, the same or a similar gameplay concept is also found in both commercial systems and video games. The Espresso Bike [1], a commercial exergaming system found in gyms, has certain modes where the user is free to explore a VE and collect coins while exercising on a stationary bicycle. The same concept is also found in video games such as Mario Kart, a go-kart racing game series.

Game Levels

There are three distinct levels in the game, as shown in Table 3. When the game starts the participant is shown what I refer to as a Wait Screen level. This type of level contains instructions for the participant about the game controls and a reminder about what they should do in the Experiment Condition level.

Table 3: Levels in the game and their purpose.

| Level Name | Purpose |
|----------------------|--|
| Tutorial | Familiarize participants with the game controls. |
| Wait Screen | Enforce a five min. break between experiment conditions. |
| Experiment Condition | Provide a setting to test the experiment hypothesis. |

Figure 6 shows the order in which a participant experiences the levels. The start of the experiment is a Wait Screen level. Here the participant can read the instructions and proceed immediately to the Tutorial level. The Tutorial level (Figure 7) serves two purposes: (1) to familiarize participants with the game controls,

and (2) to gather baseline heart-rate data from the participant.

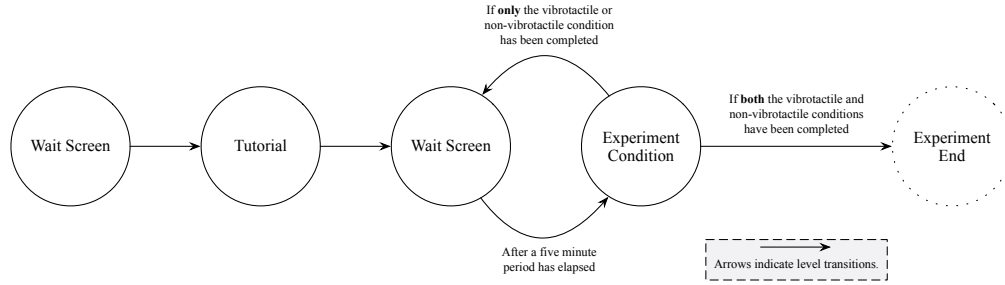


Figure 6: The order the participant experiences the levels of the game.

After the Tutorial level is finished, the participant is shown another Wait Screen level. However, this time the Game Director (Section 4.1.2) sets a timer enforcing a five minute cooldown period before the participant can continue to the Experiment Condition level. Once the Game Director raises an event signaling that the timer has elapsed the player can continue to the Experiment Condition level. This process repeats until the participant has experienced both the non-vibrotactile and vibrotactile experiment conditions. The Wait Screen and Experiment Condition levels are reused for both conditions of the experiment.

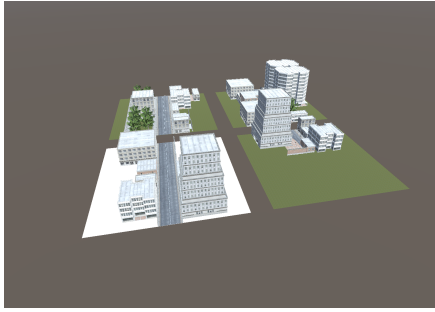
Game Level Generation

For each participant the game level is generated from a collection of pre-designed game objects I refer to as tile(s). Each tile (Figure 8a) has 3D models such as: buildings, roads, and scene decorations (e.g. signs and trees) placed on them as in Figure 8b. When a level is loaded, ten tiles are randomly selected from a list of available tiles and placed sequentially in front of the player by the *GenerateTrack* script before the scene is displayed on the HMD. The *GenerateTrack* script keeps a reference of all the tile game objects that it has instantiated. As the participant progresses through the game a separate script called the *Doorman* increments a counter in the *GenerateTrack* script when the participant leaves one tile and enters another. Once the counter reaches a preset threshold, the *GenerateTrack* script



Figure 7: The Tutorial level

will add a new tile in front of the most recent tile, while removing the oldest tile in the sequence. This process of adding and removing tiles continues for the duration of the Experiment Condition level.



(a) Four tile variants used in the exergame.



(b) A generated game level.

Figure 8: Tiles are selected randomly to generate a game level.

Game Collectible Placement & Triggering Haptic Feedback

Once the game level is generated, the game's collectibles need to be placed. To keep the gameplay less predictable the collectibles are placed for the participant as they progress through the Experiment Condition level. This is done by placing

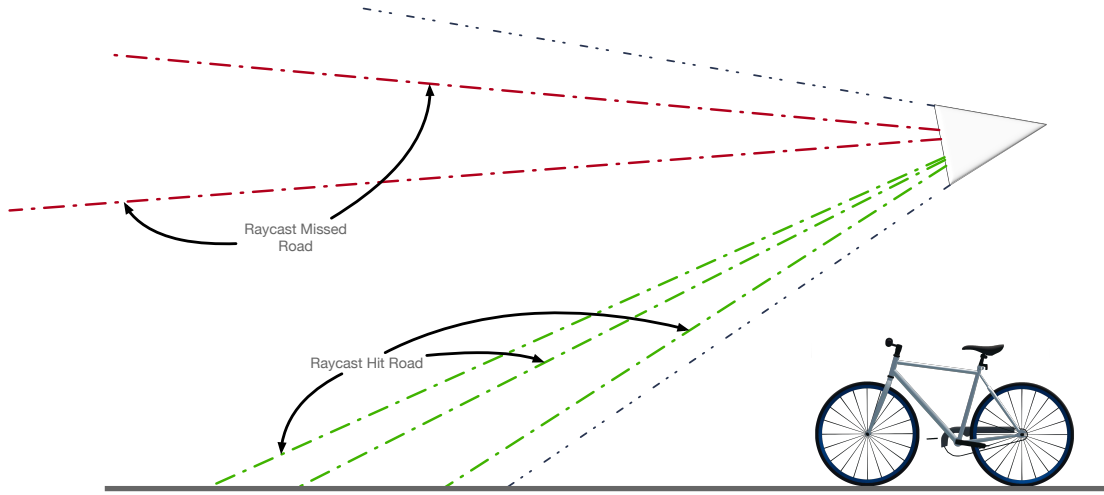


Figure 9: Generating game collectibles during game play.

above the virtual bicycle, a game object that moves in sync with speed and turns the participant makes. This game object always faces forward, relative to the player's starting position. As the participant pedals, the game object casts several rays into the VE. As shown in Figure 9, if the ray cast intersects the road, it is considered to be successful and a collectible is placed at the intersection between the ray and the road; otherwise it has no effect on the the game. A successful ray cast will always generate a collectible. However, when the collectible is placed, it has a 50% chance to be active. Active collectibles can be picked up by the player and will play a sound when collected and possibly trigger vibrotactile feedback. The collectibles themselves are responsible for calling the Game Director to trigger vibrotactile feedback for the front and rear motors (Section 4.2.3).

The number of rays cast into the virtual environment is computed following Equation (8) and depends on the speed v the participant is pedaling, as reported by the Bike Controller. If v is nearly zero no ray casts are made, so as to not overwhelm both the participant and the computer with collectibles. Otherwise, if the participant is moving slowly, as many as six ray casts can be produced each second with the amount decreasing to two ray casts if they pedal faster.

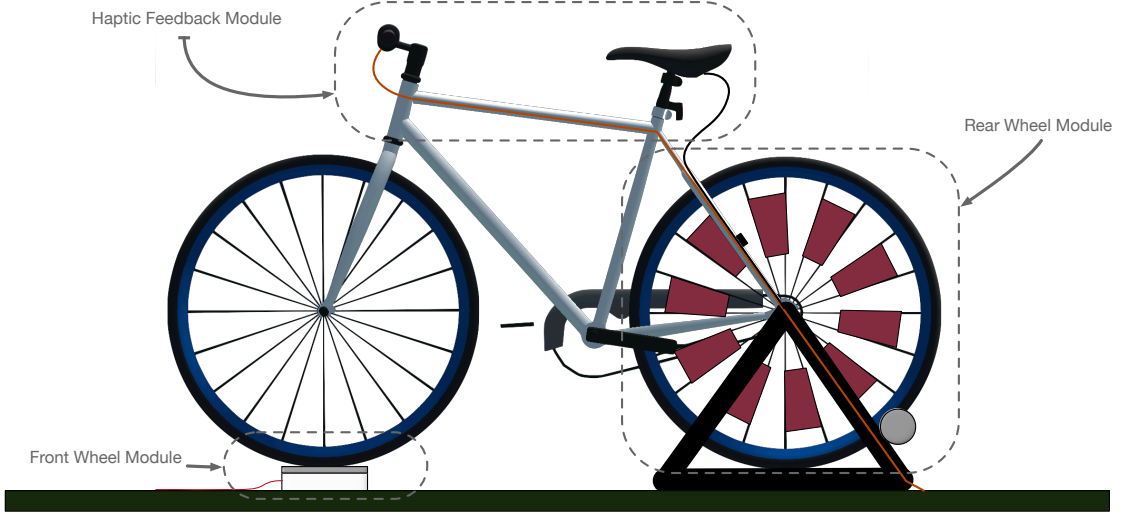


Figure 10: The system's hardware modules (excluding the Heart Rate module).

$$n = \lfloor 6e^{\left(\frac{\min(v)}{10}\right)} \rfloor \quad (8)$$

4.2 Hardware Modules

Several hardware modules were built to replicate the user's movement on the physical bicycle, collect heart-rate data, and trigger the motors needed to produce a tactile sensation. Each of the hardware modules uses an Arduino to communicate with the computer via a serial port. The Arduino platform was chosen because of the ease with which electronic designs can be prototyped, wide support for accessories, and good library support from the Arduino community. The following four modules make up the hardware side of the system: the (1) Front Wheel module, (2) Rear Wheel module, (3) Haptic Feedback module, and (4) Heart Rate module. Three of these modules are illustrated in Figure 10.

4.2.1 Front Wheel Module

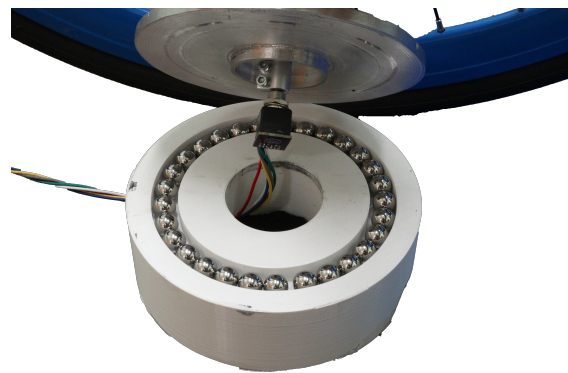
The Front Wheel module (Figure 11) measures the angle of the front wheel relative to an initial position when the exergame starts. To measure the angle, I chose an absolute rotary encoder since it can give an accurate angle position

without prior calibration. The encoder is connected to an Arduino board which is programmed with code which queries the rotary encoder to obtain a current reading.

The encoder sits inside a 3D printed case (Figure 11b) which I designed in Autodesk, a CAD software program, for this module of the system. The case consists of the body and a circular plate which is coupled to the encoder. Between the body and plate are several steel balls which allow the plate to slide over the plastic body. I originally intended to produce the entire encoder case via 3D printing, however I found that the way the plate was printed would cause the encoder to detach from the plate after a handful of uses. Eventually, because of this, I decided to use a CNC machine available at the University of Rhode Island to machine the plate out of aluminum. By resting the front wheel of the bicycle on top of the plate (Figure 11a) I am able to measure the displacement of the front wheel and reflect any changes to the angle in the VE.



(a) With the bicycle resting on top.



(b) The parts making up the module.

Figure 11: Front Wheel module

4.2.2 Rear Wheel Module

The purpose of the Rear Wheel module is to measure the speed the user is pedaling at. Figure 12 shows the two components that make up the Rear Wheel



Figure 12: An illustration of the IR sensor and blockers of the rear wheel module.

module, an IR Break Beam Sensor and IR Beam Blockers. To measure the speed, I used an Adafruit IR Break Beam Sensor³ that is fixed to the rear frame of the bicycle using zip ties. The IR Break Beam Sensor (IR sensor) is a digital sensor composed of an emitter and a receiver. The emitter constantly sends out a beam of infrared light which is detected by the receiver placed a short distance away from it. When the receiver detects that the beam is unbroken (i.e. it has a clear view of the emitter) it outputs a logic high signal; likewise, when the the receiver's view of the beam is obstructed, it changes its output to a logic low signal. This sensor, like all the other hardware modules of this system, is connected to an Arduino board and is registered on the connected computer as a serial device.

When the rear wheel spins, the IR sensor's beam is broken by several IR Beam Blockers. These IR Beam Blockers are painted sections of tape wrapped around two spokes at equal intervals around the wheel, as illustrated in Figure 12. The Arduino board measures the time between breaks in the IR beam. Since the arc between the start of two of the IR Beam Blockers is fixed, the Bike Controller (Section 4.1.2) can use the time measurement to estimate the speed of the wheel.

³<https://www.adafruit.com/product/2167>

4.2.3 Haptic Feedback Module

Vibrotactile feedback can be produced by two types of motors: eccentric rotating mass (ERM) motors and linear resonant actuators (LRA) [2]. An ERM motor is a standard direct current (DC) motor with an off-center mass attached to the rotor. As the motor is powered, it rotates and a vibrational force is generated due to the attached, off-center mass [3]. By varying the voltage, the speed of the motor, and thus vibration, can be controlled. This is the style of motor used in this system.

While an ERM motor is assembled from a commonplace DC motor, an LRA is built and operates somewhat differently. The primary components of an LRA are a permanent magnet, wire coil, spring, and a mass [4]. The mass and magnet are attached to each other and placed in front of the spring. Unlike an ERM motor, which can be powered using a simple DC signal, an alternating current (AC) signal needs to be used for an LRA to function properly. The AC signal creates a magnetic field in the wire coil causing the magnet to push back and forth against the spring, creating vibration.

I chose to use ERM type motors over LRA since the former can produce a higher vibration strength [5]. LRA motors are better suited for smaller devices or applications where the lifetime of the motor is important. When testing the Haptic Feedback module early in its development, I found that both LRA type and small ERM motors did not produce a strong enough vibration to be felt when pedaling on the bicycle. Consequently, I opted to use larger ERM motors in the final implementation of this module.

In order to produce the vibration when the user encounters a collectible in the vibrotactile feedback experiment condition described in Section 3.4, three ERM motors (Figure 13) need to be controlled by the software modules. An Arduino



Figure 13: Haptic Feedback module

board is again used to provide a convenient bridge between the PC and the hardware, however an Arduino board alone cannot supply the power required to drive the motors. Instead a motor control board produced by Pololu Electronics is attached to the top of the Arduino board and is used to drive the three motors and power them. The power for the motors is supplied from a 12 volt 5 ampere wall adapter which provides a consistent source of power across experiment sessions. This adapter is connected directly to the motor control board to avoid damaging the Arduino board. The wall adapter was chosen instead of battery supply to ensure that the strength of the motors is consistent across experiment sessions.

The three motors are split between the front and rear of the bicycle. Two smaller ERM motors (Figure 13a) are placed on the handlebars, due to size constraints, and a larger ERM motor (Figure 13b) is placed in the rear underneath the seat. The two smaller motors are connected to the motor control board in parallel so that they run simultaneously when the Game Director (Section 4.1.2) triggers them. The larger motor is connected directly to the control board. Both the front and rear motors can be triggered by the Game Director when a user encounters a manhole collectible. When either the front or rear wheel of the virtual bicycle collides with an active collectible, the appropriate waveform is played. For example, if the front wheel of the bicycle collides with with an active collectible,

then only the waveform for the handlebar motors will be played.

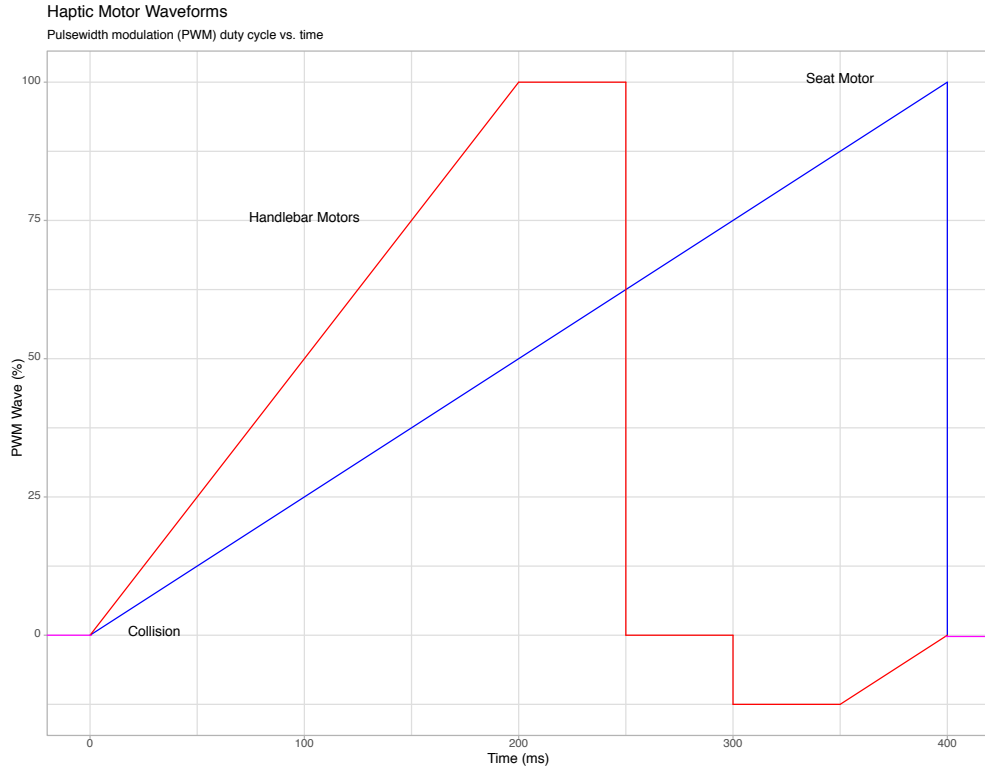


Figure 14: The two signals generated to drive the motors.

The plot in Figure 14 shows the changes in the pulse-width modulation (PWM) duty cycle over time in milliseconds. A PWM duty cycle refers to the amount of time that a digital signal is high vs. low over a fixed period of time [6]. An Arduino pin has a frequency of around 490 Hz which has a period of 2.041 ms [7]. For instance a duty cycle of 100% is the equivalent of sending a signal that is always high, while a duty cycle of 50% on the Arduino is a signal that is high for roughly 1 ms and low for another millisecond.

The vibrations of the handlebar and seat motors are driven by two different waveforms to give the sensation of running over something. The seat waveform, the blue line in Figure 14, is the simplest of the two: Over the course of 400 ms the motor is driven to 100% duty cycle and then abruptly stopped. The waveform for

the handlebar motors, the red line in Figure 14, is more complicated. When the Game Director triggers a pulse the handlebar motors are driven to a 100% duty cycle in 200 ms and held there for 50 ms. To avoid damaging the motors, both are stopped for 50 ms before running them in reverse at a 13% duty cycle for another 50 ms and stopping them again.

4.2.4 Heart Rate Module

The system is capable of recording a participant's heart rate through the Heart Rate module. Early versions of this module used a wired pulse sensor⁴. However, I decided against this approach because the sensor readings were prone to error if the wire moved. The Heart Rate module uses a Polar OH1 optical heart rate sensor⁵ which communicates over Bluetooth as a peripheral implementing the heart rate service.

To connect to the OH1, I use an Adafruit Feather nRF52 Bluefruit LE⁶ (Feather). The Feather is an electronics prototyping board similar to an Arduino with a smaller form factor and slightly different functionality. It enumerates itself as a serial port when connected to a computer allowing data to be read from and written to it.

On startup, the Feather scans for the OH1 sensor and waits for the Game Director (Section 4.1.2) to send a Participant ID. The Feather uses an add-on board with a real-time clock & micro-SD card to create a comma-separated values (CSV) file, a type of file that uses commas to separate entries from each other, on the device. This file is where the heart rate the OH1 measures is recorded. The measurement is time-stamped based on the current time of the real-time clock. The Feather will continuously record the heart rate sent by the sensor until the

⁴<https://www.sparkfun.com/products/11574>

⁵<https://www.polar.com/us-en/products/accessories/oh1-optical-heart-rate-sensor>

⁶<https://www.adafruit.com/product/3406>

board is reset, allowing a new file with a new participant ID to be created and written to. If the OH1 goes out of the connection range of the Feather, no data will be recorded. The Feather also receives data from the game while the experiment is running, which is described in Section 4.1.2.

4.3 Summary

To conclude this chapter has reviewed the implementation of the system which has been implemented to conduct the experiment described in Chapter 3. The system can be divided into two groups of modules: (1) the hardware modules and (2) the software modules. Section 4.1 reviewed the software modules of the system and Section 4.2 reviewed the hardware modules.

The software modules are implemented in Unity and consist of the Serial Port Interface, the Game Controller, and the Exergame. The Serial Port Interface manages serial communications between the hardware modules and the Game Controller. While the Game Controller module is tasked with managing the game logic of the Exergame, the logic of the experiment, and applying the data received from the Serial Port Interface to a virtual bicycle in the Exergame. The Exergame module contains the code for generating a game level at run-time and procedurally placing game collectibles.

The hardware modules translate the movements and actions on the bicycle to data which can be used by the software modules or for later analysis. All the hardware modules communicate with a computer through an Arduino or closely related device. The Front Wheel and Rear Wheel modules measure the angle of the front wheel and speed of the bike which is used by the bicycle model in the Game Controller module. The Haptic Feedback module provided vibrotactile feedback when a user collides with a game collectible in the virtual world. To provide vibrotactile feedback three ERM motors are used, since they provide a

stronger vibration than LRA motors. The last hardware module is the Heart Rate module which records a participants' heart rate through a Bluetooth heart rate monitor and stores it for later analysis or use.

List of References

- [1] Interactive Fitness, "Espresso Bikes," Accessed: 2018-11-06. [Online]. Available: <https://espresso.com/Home>
- [2] Precision Microdrives, "Vibration Motors," Accessed: 2019-02-16. [Online]. Available: <https://www.precisionmicrodrives.com/vibration-motors/>
- [3] Precision Microdrives, "Eccentric Rotating Mass Vibration Motors - ERMs," Accessed: 2019-02-16. [Online]. Available: <https://www.precisionmicrodrives.com/vibration-motors/eccentric-rotating-mass-vibration-motors-erms/>
- [4] Precision Microdrives, "AB-003 : Driving Linear Resonance Vibration Actuators," Accessed: 2019-02-18. [Online]. Available: <https://www.precisionmicrodrives.com/content/ab-003-driving-linear-resonance-vibration-actuators/>
- [5] Precision Microdrives, "Integration Guide: Haptic Feedback and Vibration Alerting for Handheld Products," pp. 1–20, Accessed: 2019-03-18. [Online]. Available: https://www.precisionmicrodrives.com/wp-content/uploads/2016/01/haptic-feedback-vibration-alerting-for-handheld-products_0.pdf
- [6] JORDANDEE, "Pulse Width Modulation," Accessed: 2019-03-19. [Online]. Available: <https://learn.sparkfun.com/tutorials/pulse-width-modulation/all>
- [7] Arduino, "Analogwrite," 2019, Accessed: 2019-03-19. [Online]. Available: <https://www.arduino.cc/reference/en/language/functions/analog-io/analogwrite/>

CHAPTER 5

User Study and Data Analysis

In this chapter I present the results of a user study I have conducted to evaluate the system and provide evidence towards my hypothesis. As of this writing, I have recruited ten participants, only seven of whom were eligible to participate. This chapter is divided into two parts: Section 5.1 shows the format of the data generated by the system and Section 5.2 presents a preliminary analysis of the data gathered from the experiment thus far. Unfortunately due to time constraints, I could not analyze the heart rate data collected from the experiment. Instead a plot of the heart rate data collected by the system is presented in Section 5.1.

5.1 System Data

The only data generated by the system that is recorded is from the Heart Rate module presented in Section 4.2.4. As previously mentioned, the data from the Polar OH1 heart rate sensor is recorded on a micro-SD card on the Feather device in a CSV format. The CSV file has four columns: `unix_time`, `heart_rate`, `current_scene`, and `haptics_on`. Figure 15 shows an example of data generated by the module.

| <code>unix_time</code> | <code>heart_rate</code> | <code>current_scene</code> | <code>haptics_on</code> |
|------------------------|-------------------------|----------------------------|-------------------------|
| 1549736499 | NA | WaitScreen | True |
| 1549736499 | 94 | WaitScreen | True |
| 1549736500 | 94 | WaitScreen | True |
| 1549736501 | 93 | WaitScreen | True |
| 1549736502 | 92 | WaitScreen | True |
| 1549736503 | 91 | WaitScreen | True |
| 1549736504 | 90 | WaitScreen | True |

Figure 15: An example CSV file generated by the system.

The timestamp in the `unix_time` column is generated from the real-time clock on-board the Feather device. The Feather queries the OH1 sensor at one second intervals and records the value recieved into the file. On a scene is change (Section 4.1.3), the Game Director will notify the Feather, writing the name of the scene into the CSV. Finally the Game Director will notify the Feather if the Haptic Feedback module is turned on or off.

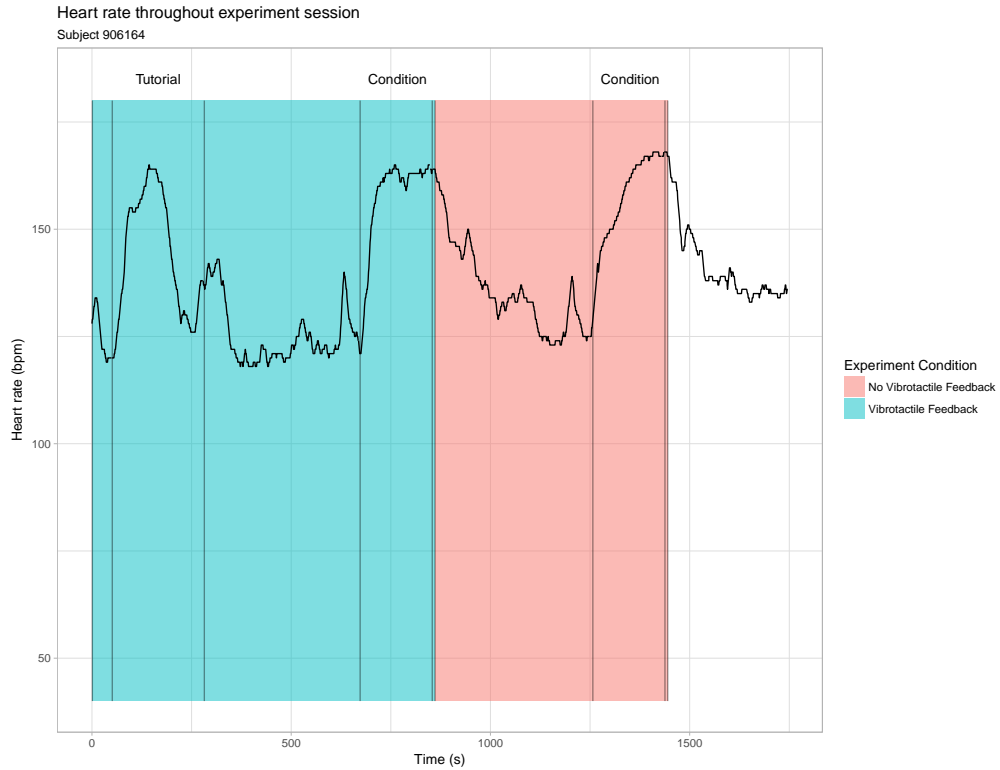


Figure 16: Heart rate data recorded by the system.

The line plot in Figure 16 showing a participant's heart rate over time uses all the information recorded in a participant's CSV file. The x and y-axes respectively represent the time in seconds and the recorded heart rate value in beats per minute (bpm). The blue rectangle represents the period of time when the Haptic Feedback module was enabled; conversely the red rectangle represents when the Haptic Feedback module was off. Looking closely at the plot, there are several vertical

lines spaced over the x-axis. These lines represent the level transitions discussed in Section 4.1.3, the intervals representing the Tutorial and Experiment Condition levels are labeled. This type of data could be analyzed using linear regression. By isolating the two line segments underneath each of the “Condition” labels and fitting a linear model to the data, the slope and intercept between the two lines can be compared.

Walking through the plot, from zero to about 30 seconds is the first Wait Screen level of the experiment. An interesting observation here is that, even though the participant has not played the exergame yet, their heart rate is already quite high. This could be due to nervousness on the part of the participant. Between 30 seconds to 260 seconds is the Tutorial level of the experiment, followed by a break period. Another interesting observation from this plot is the bpm spike before both condition intervals. This could be a reaction the participant had to being told that the break was almost over, or something else entirely.

5.2 Data Analysis

This section presents an analysis of the data gathered from the user study. Section 5.2.1 presents the demographics of the sample, including experience with virtual reality and video games, exercise frequency, and biking frequency. An analysis of the IMI and immersion questionnaires is presented in Section 5.2.2. Finally, Section 5.2.3 covers the responses to the post-experiment questionnaire.

5.2.1 Pre-Experiment Questionnaire

Currently there are seven participants I have collected data from. All, as of now, were a convenience sample drawn from the Department of Computer Science and Statistics at the University of Rhode Island. Of the seven participants five are male and two are female. The average age of a participant is 23 ranges from be-

tween 20 to 30. Table 4 shows descriptive statistics for participant ages, experience with virtual reality, and experience with video games.

Table 4: Descriptive Statistics for the Pre-Experiment Questionnaire

| | Min. | 1st Qu. | Median | Mean | 3rd Qu. | Max. |
|-----------------------------------|-------|---------|--------|-------|---------|--------|
| Age | 20.00 | 21.00 | 21.00 | 22.86 | 23.50 | 30.00 |
| Virtual Reality Experience | 0 | 16.00 | 22.00 | 23.14 | 29.00 | 50.00 |
| Video Game Experience | 24.00 | 34.50 | 50.00 | 58.86 | 84.50 | 100.00 |

Most reported they had little prior experience with virtual reality. Given how recently the technology became commercially available (Section 2.3) this is not surprising. The reported experience with video games varied considerable more, as shown in Figure 17.

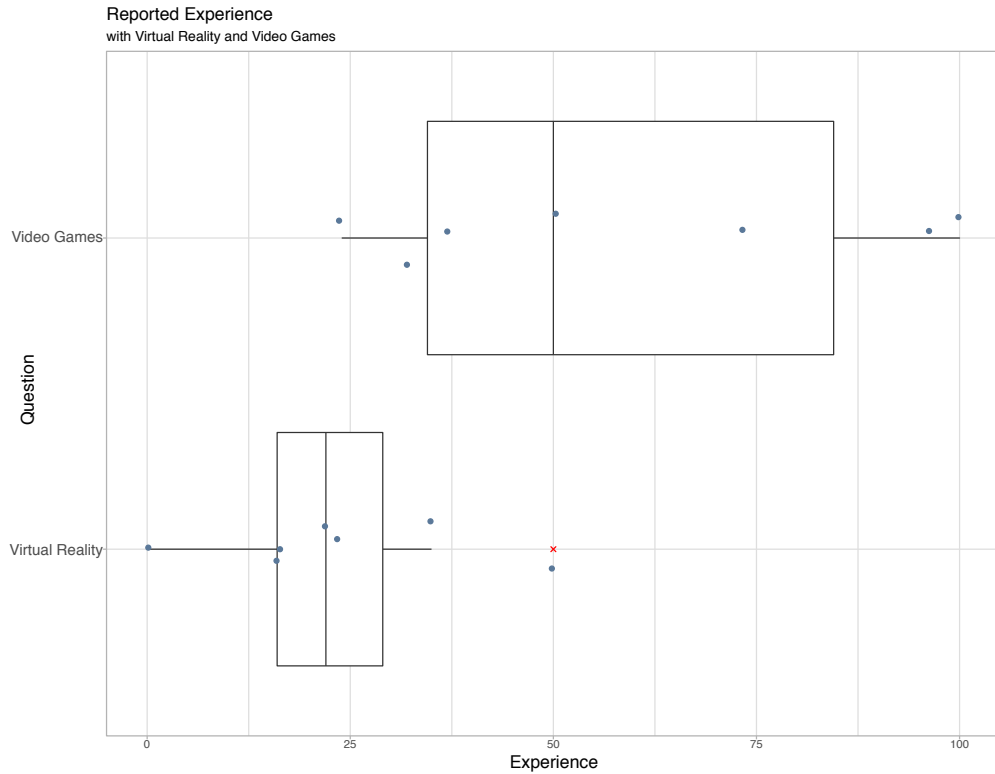


Figure 17: Reported experience with video games and virtual reality.

On the pre-experiment questionnaire (Appendix A.1), participants were asked what genres of video games they typically played, their frequency of aerobic exer-

cise, and how often they ride a bicycle. Table 5 shows the responses to the latter two questions. Most participants exercised once a week or more often; however none of them frequently rode a bicycle.

Table 5: Exercise frequency reported by participants.

| Question\Answer | Less than once a month | Once a month | A few times a month | About once a week | A few times a week | Every day |
|---|---------------------------|-----------------|------------------------|----------------------|-----------------------|-----------|
| How often, on average, do you perform aerobic exercises, such as running or biking? | 2 | 0 | 1 | 2 | 2 | 0 |
| Over the course of a month, how often do ride a bicycle? | 6 | 1 | 0 | 0 | 0 | 0 |

The video game genres participants played (Table 6), ranked from most to least popular are: (1) Adventure, (2) Action, (2) Strategy, (4) Role-playing, (5) MMO, (6) Simulation, and (6) Sport. Both the simulation and sport genres were tied for last. The fact the sport genre is one of the least popular genres reported by participants is interesting. Recalling the barrier of access described in Brown and Cairns’ paper, players must like to play the genre game in order to become engaged with the game [1].

Table 6: Participants preference of game genres.

| Question\Answer | Adventure | Action | Strategy | Roleplaying | MMO | Simulation | Sport |
|--|-----------|--------|----------|-------------|-----|------------|-------|
| What genre of games do you typically prefer to play? | 5 | 4 | 4 | 3 | 2 | 1 | 1 |

5.2.2 Intrinsic Motivation and Immersion Questionnaire

In this section I present an analysis of the intrinsic motivation and immersion questionnaires. For both questionnaires I computed Cronbach’s alpha using Equation (9) [2].

$$\alpha = \frac{K}{K-1} \left(1 - \frac{\sum_{i=1}^K \sigma_{Item_i}^2}{\sigma_{Total}^2} \right) \quad (9)$$

Cronbach’s alpha is a measure of the internal consistency of a questionnaire (i.e. are the questions all measuring the same concept). In Equation (9), K should be substituted with the total number of items on the questionnaire. The variance for

the each item on the questionnaire is summed and divided by variance of the total scores for each respondent. The responses to both questionnaires were compared using the Sign test and Wilcoxon signed-rank test, which are discussed later.

Intrinsic Motivation Questionnaire

In Chapter 3, I discussed how intrinsic motivation is measured during the experiment. The intrinsic motivation questionnaire is the interest/enjoyment subscale of the IMI. Participants were given this questionnaire after both experiment conditions and were free to take as long as the needed to complete it. As also discussed in Chapter 3, to score the intrinsic motivation questionnaire the scores for each of the questions should be averaged together. Questions which express a negative sentiment (e.g. “I thought the exergame/haptic exergame was boring.”) should be reversed scored, that is, the score that was reported should be subtracted from the highest score on the scale. Figure 18 shows a box and whiskers plot for the results of the intrinsic motivation questionnaire after following the scoring procedure.

As mentioned at the beginning of this section I computed Crombach’s alpha, although the interest/enjoyment subscale of the IMI has been previously validated. I ran the test on both the regular and vibrotactile variants of the questionnaire used. I also pooled both variants of the intrinsic motivation questionnaire used in the experiment and tested that as well. I found an α of higher than 0.9 for all three questionnaires: regular ($\alpha = 0.91$), haptic ($\alpha = 0.94$), and pooled ($\alpha = 0.93$) indicting high internal consistency.

To determine if there is enough evident to support my hypothesis that haptic feedback does increase user motivation, I performed the Sign test and Wilcoxon signed-rank test on the averaged scores from the intrinsic motivation questionnaire. The Sign test and Wilcoxon signed-rank test are called non-parametric tests. Non-

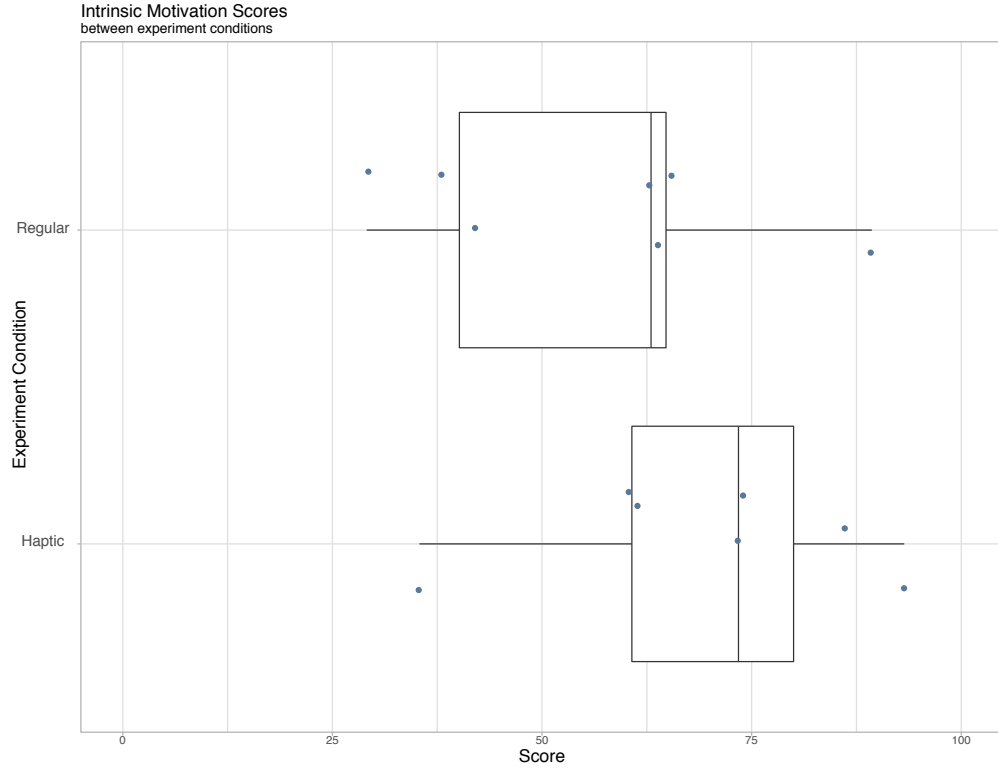


Figure 18: Intrinsic motivation scores between experiment conditions.

parametric tests can be used when the size of a sample is small and the distribution of the variable being examined is unknown [3]. Since I am comparing scores between the regular and haptic exergame for the same participant, the scores are dependent measurements.

For both the Sign test and Wilcoxon signed-rank tests the null hypothesis is that the median difference between the two groups being analyzed is zero. The alternative hypothesis for both tests is that the median difference in first group (i.e. regular exergame) is less than the median difference in the second group (i.e. vibrotactile exergame). Formally, the hypotheses for the tests are:

$$H_0 : M_1 = M_2,$$

$$H_1 : M_1 < M_2 \quad \alpha = 0.1.$$

M in this case represents the population median, M_1 is the regular exergame

group, and M_2 is the vibrotactile exergame group. The first test I performed was the Sign test. To perform this test, I used the R package “BSDA,” which provides a function of the same name [4]. The p-value of the test was computed by the package as $p = 0.0625$, with this value the results are significant. Since the results of the Sign test show there a p-value of $p = 0.0625 < 0.1$, I am able to reject the null hypothesis in favor of the alternative.

The second test conducted was the Wilcoxon signed-rank test. The R “stats” package provides an implementation of this test, which I used to compute the p-value for this test. The results of the one-sided test showed a p-value of 0.02344. Based on this test, $p = 0.02344 < 0.1$ so the null hypothesis is rejected in favor of the alternative.

From the results of both the Sign test and Wilcoxon signed-rank tests, there appears to be statistically significant evidence to support my hypothesis that vibrotactile feedback can increase intrinsic motivation in exergames. However, due to the small sample size of the study there is a greater chance for bias in the sample. Further study is warranted before claiming the results generalize to a larger population.

Immersion Questionnaire

The questions on the immersion questionnaire are drawn from the questionnaire developed by Jennett et al. [5]. As stated in Section 2.2 the term immersion is used in this thesis as a psychological state with multiple levels and the following characteristics: “lack of awareness of time,” “loss of awareness of the real world,” and “involvement and a sense of being in the task environment” [5, 1]. On the questionnaire I developed I intended Questions 1, 2, 5 and 6 (Appendix A.3) to capture the concept of immersion within my exergame. Since they are all intended to represent the same concept the items should be averaged together; with the

exception of Question 6 which should be reverse scored. Figure 19 shows a box plot of the average score, which I will refer to as the immersion score, for Questions 1, 2, 5 and 6.

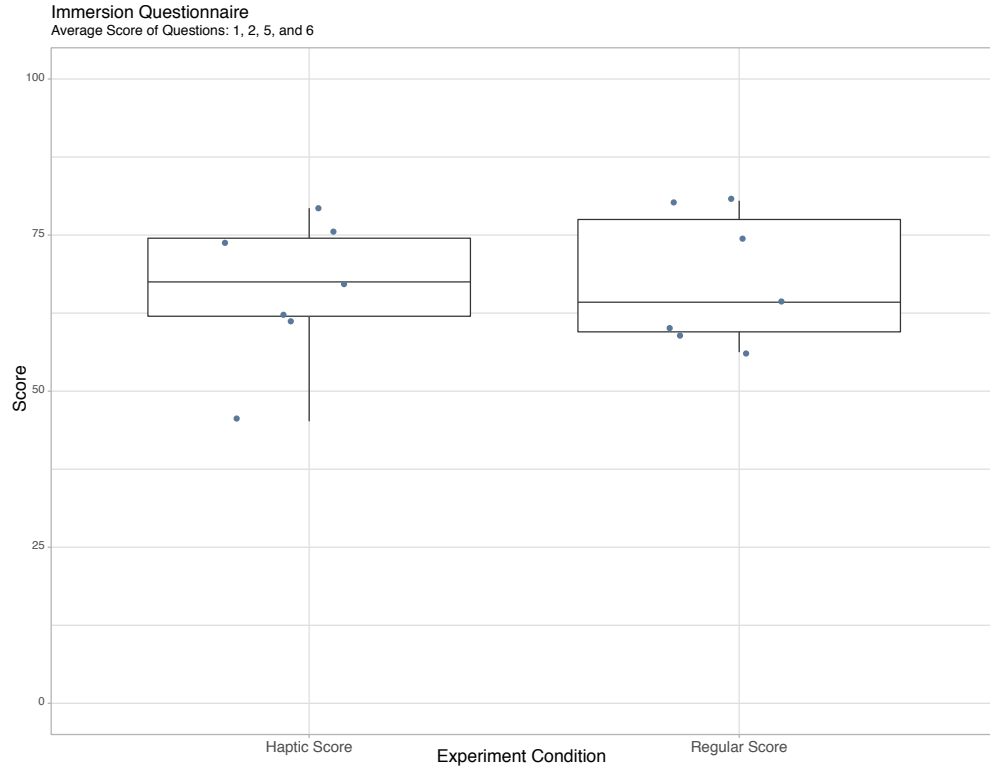


Figure 19: Immersion scores across experiment conditions.

As with the intrinsic motivation questionnaire, I computed Crombach's alpha for the four questions comprising the immersion score. Like the before I tested ran the test against the regular, haptic, and pooled versions of these questions. Unfortunately, all three tests produced an α between 0.05 and 0.21: regular ($\alpha = 0.05$), haptic ($\alpha = 0.21$), and pooled ($\alpha = 0.13$). This indicates low internal consistency for the questions making up the immersion score used. One possible issue is the low sample size of my analysis, which increases the variance of the scores in each item. Another possibility is that more questions are needed to better capture the concept of immersion with this questionnaire.

For the immersion score I compared the scores between the regular and haptic exergames using the Sign test and Wilcoxon signed-rank tests. Similar to the intrinsic motivation questionnaire the hypotheses for the tests are:

$$H_0 : M_1 = M_2,$$

$$H_1 : M_1 < M_2 \quad \alpha = 0.1.$$

Again M here represents the population median, M_1 is the regular exergame group, and M_2 is the vibrotactile exergame group.

Using the same R package, the Sign test produced a p-value of $p = 0.5$. Unfortunately I am unable to reject the null hypothesis for this test with this p-value at a significance of $\alpha = 0.1$. Performing the Wilcoxon signed-rank test on the immersion scores produced a p-value of $p = 0.5$. I am again unable to reject the null hypothesis that the median of the regular immersion score is less than the of the haptic immersion score at a significance of $\alpha = 0.1$.

Based on both of these tests there is not enough evidence to support my hypothesis that tactile haptic feedback will increase an exergame users' immersion in the game. There are a few possibilities why this occurred. Overall the low sample size likely introduced some bias into the results. As indicated in Table 5 while most of the participants exercised with some regularity, all of them rarely rode a bicycle. Another issue is, as I wrote previously, the low internal consistency of the questions used to measure immersion may not capture the concept of immersion accurately. Finally, based on the reported genres in Table 6 and in the context of the engagement level of immersion discussed in Section 2.2, it is possible that our small sample of participants did not want to engage with the exergame.

5.2.3 Post-Experiment Questionnaire

The post-experiment questionnaire consists of six questions intended to capture a participant's opinions on future use of the system, how they feel the virtual bicycle behaved, and if they experienced any symptoms of cybersickness.

Future Use Questions

There are three questions on the post-experiment questionnaire regarding future use of the system. The responses to these questions tended to express a positive sentiment towards using the exergame again. The pie chart in Figure 20 shows a breakdown of the responses to: “Using the exergame with haptic feedback would cause me to use an exercise bike more often.” Few participants responded negatively to this question, with 57.2% indicating the exergame with haptic feedback would cause them to use an exercise bike more often.

Post-Experiment Questionnaire

Using the exergame with haptic feedback would cause me to use an exercise bike more often.

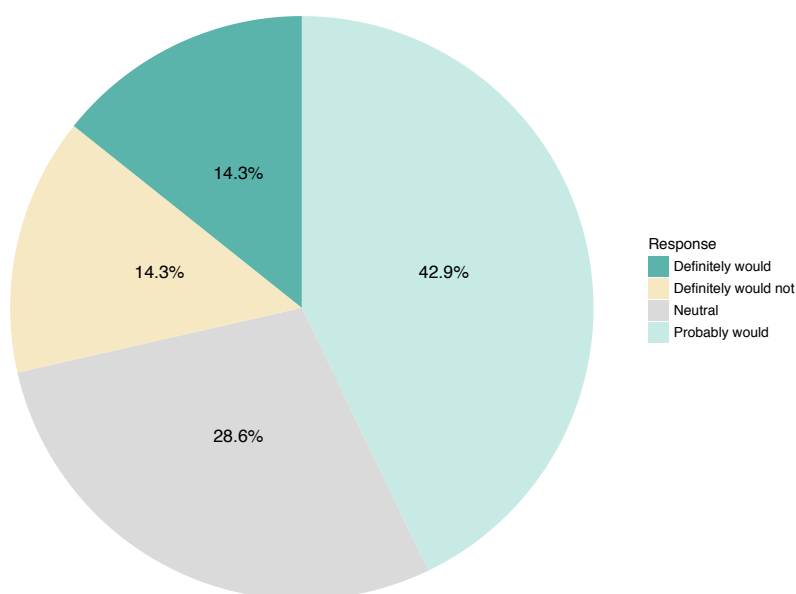


Figure 20: The first future use question.

The second question asked participant if they agreed with the statement: “Using the exergame with haptic feedback would cause me to use an exercise bike for longer.” Figure 21 shows a pie chart plotting the answers the participants gave to the question. As with the first question 57.2% of participants responded favorably to the question, indicating that it was either “Very Likely” (14.3%) or “Likely” (42.9%) the exergame would cause them to use an exercise bike longer.

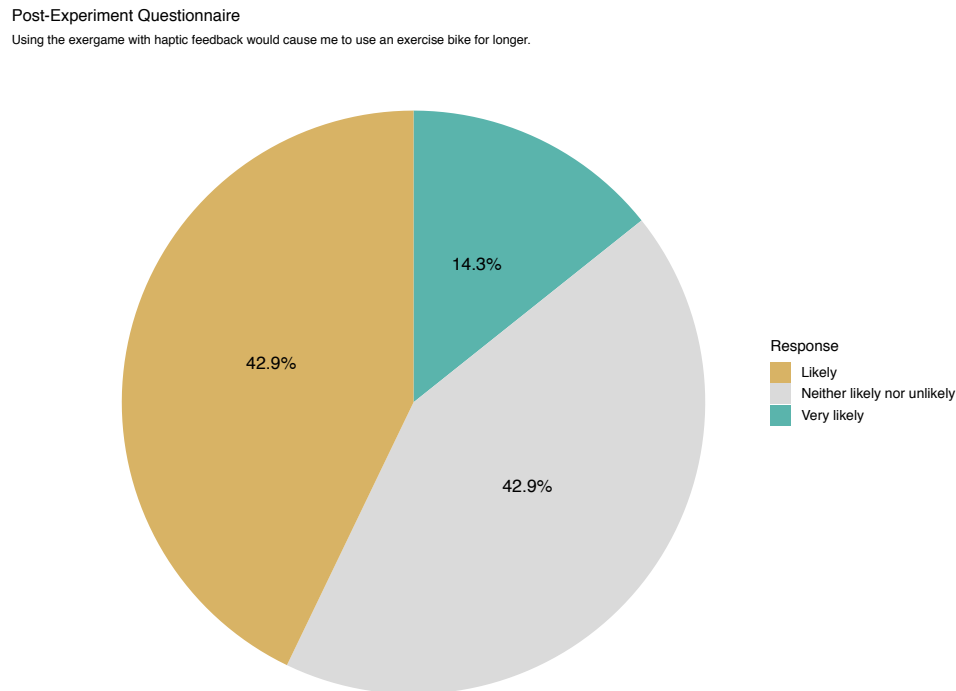


Figure 21: The second future use question.

The final question on the post-experiment questionnaire relating to future use of the system is: “Would you prefer to use an exergame with haptic feedback like the one presented in the study for regular exercise?” Responses to this question are more mixed than the first two questions. They are divided equally between “Definitely would prefer,” “Neutral,” and “Probably would not prefer.” Only a single person responded that they would definitely not want to regularly use the

system for exercise.

Post-Experiment Questionnaire

Would you prefer to use an exergame with haptic feedback like the one presented in the study for regular exercise?

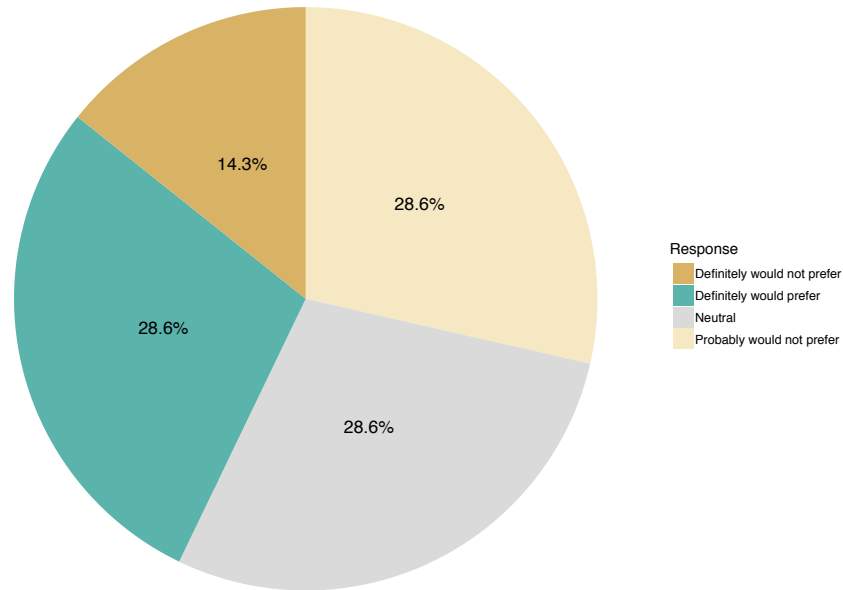


Figure 22: The final future use question.

Discussion

Taken together, the three questions above provide a window into how people might use the system for exercise. Most participants believed that this system would lead to them using an exercise bike longer and more often. However despite this, most participants reported they “Probably would not prefer” (28.6%) and “Definitely not prefer” (14.3%) to use the system for regular exercise, a large number also reported no opinion either way (28.6%).

One interpretation of these responses is that most participants see the system and accompanying exergame as only a game or healthier alternative to traditional video games, rather than something that could be used for exercise. Another interpretation is that participants see the system as equipment they would use

less frequently for exercise compared to a regular exercise bike or treadmill (e.g. for a weekend workout as opposed to during the week when they have less time). When they would use the system they would use it for a longer period of time than a traditional exercise bike. Finally, since all of the participants reported low experience with VR, it could be that most participants find the system new and interesting, but cannot see themselves using it for exercise on a regular basis.

I believe that part of the reason why most participants reported they would not prefer to use the system for regular exercise is that many had trouble operating the system initially. This reached the point where the investigators present would stand on either side of the participant to catch them if they fell off the bicycle. During early testing of the system with the research staff, we noticed that the staff who rode bicycles frequently found the system difficult to adjust to, while those who did not had an easier time.

Bicycle Realism

The question concerning how the virtual bicycle behaved compared to a real bicycle received favorable responses. Figure 23 shows a pie chart with the responses to the question: “Did you feel that the virtual bicycle behaved the same as a real bicycle?” This question was answered as a seven point Likert item from “Strongly Disagree” to “Strongly Agree”. Most participants (71.5%) agreed in some measure that the virtual bicycle behaved correctly, while only a single person (14.3%) did not feel this was true. The remaining participant expressed no sentiment to this question.

As mentioned earlier, during testing I noticed that many participants had trouble operating the system initially, although they would eventually adapt. Given the observed difficulty using the system, the fact that most participants agree that the virtual bicycle behaved as they would expect a real bicycle to behave is

Post-Experiment Questionnaire

Do you feel that the virtual bike behaved similarly to a real bike?

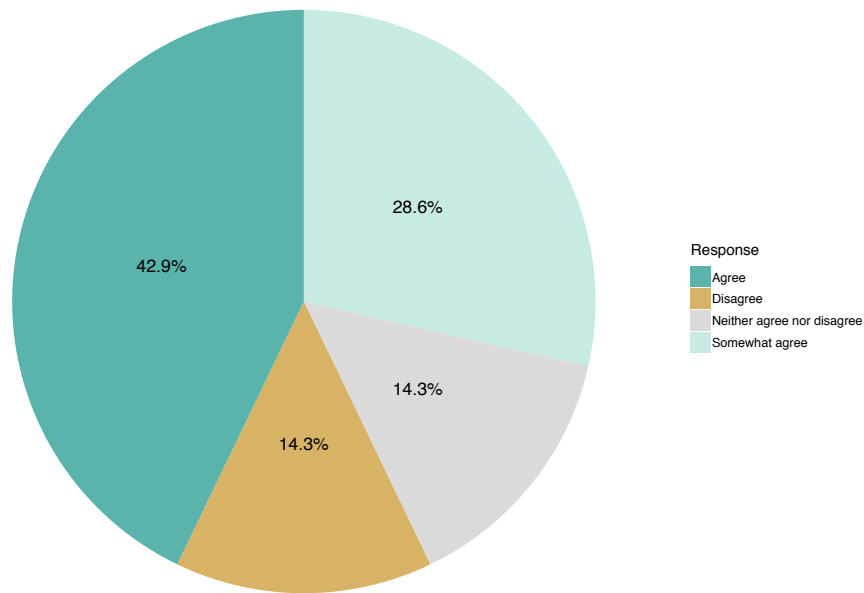


Figure 23: How participants felt the virtual bicycle behaved.

interesting. I think this suggests three ideas regarding the system:

- The mathematical model used for the virtual bicycle is correctly implemented and calibrated to the dimensions of the real bicycle.
- Both the Front Wheel module and Rear Wheel module work correctly and provide accurate data to the model.
- The issues I observed during testing are due to some aspect of the physical bicycle not matching the expectations of the participant.

The fact that most participants agreed with this question provided support for the first two bullets. If either the model or sensors were producing or consuming inaccurate data, then the virtual bike would behave incorrectly. This premise and that no participants reported they strongly agreed with the question provides

some support for the final bullet. I believe that one major aspect is that the physical system does not allow the participant to lean into a turn, as they would on a real bicycle. In fact during the Tutorial level and early in the first Experiment Condition level, many participants would attempt to tilt the system in the direction they were turning, usually led to them almost falling off the bicycle.

Cybersickness

Cybersickness is an illness that occurs occasionally in when a user interacts with a VE in VR though an HMD or other system [6]. Symptoms of cybersickness are similar to motion sickness and include disorientation, nausea, dizziness, vomiting, and headaches among others [7]. There are three popular theories for explaining cybersickness; The most popular is sensory conflict theory [7]. Sensory conflict in VR is thought to occur when the visual system, which processes what we see, and vestibular system, which deals with the perception of motion, observe conflicting information that the body can not interpret, thus leading to symptoms of cybersickness [7, 6]. In the case of this bicycle system, visually the person sees themselves moving on the bicycle, while their vestibular system does not experience any motion, thus leading to conflicting reports.

The focus of this experiment was not on examining the effects of cybersickness on participants. However, I did expect some participants to experience mild to moderate symptoms. The responses to the question: “Did you experience any of the following?” showed most participants did experience one or more symptoms of cybersickness, as shown in the bar plot of Table 7.

Table 7: Symptoms of cybersickness reported by participants.

| Question\Answer | Light headedness | Disorientation | Nausea |
|--|------------------|----------------|--------|
| Did you experience any of the following during the experiment? | 5 | 4 | 4 |

Only one participant, who reported they rode a bicycle once a month, did not report any symptoms. They did however report in the “Other” comment box for the question the following: “Hard turns were a bit weird ti [sic] get used to. Felt fine once I got used to it[.]”

5.3 Summary

In conclusion, this chapter has examined the data generated by the system and presented an analysis of the survey responses gathered from conducting the experiment laid out in Chapter 3. The data presented in Section 5.1 and responses to the post-experiment questionnaire, reviewed in Section 5.2.3, suggest that the system described in Chapter 4 is functioning as intended. The user study presented here examined a sample of seven people taken from the Department of Computer Science & Statistics.

My analysis of the intrinsic motivation questionnaire found significant results supporting my hypothesis vibrotactile feedback can increase a users’ intrinsic motivation. Unfortunately the analysis of the immersion questionnaire did not find supporting evidence for my hypothesis that vibrotactile feedback will increase immersion in an exergame. In both cases further study is warranted due to the small sample size of the study.

List of References

- [1] E. Brown and P. Cairns, “A Grounded Investigation of Game Immersion,” in *Proceedings Extended Abstracts of the 2004 Conference on Human Factors and Computing Systems*. Vienna, Austria: ACM Press, 2004, pp. 1297–1300.
- [2] R. F. DeVellis, “Reliability,” in *Scale Development*, 2nd ed. London: SAGE Publications, 2003, ch. 3, pp. 27–47.
- [3] R. B. D’Agostino Sr., L. M. Sullivan, and A. S. Beiser, “Nonparametric Tests,” in *Introductory Applied Biostatistics*, 1st ed., C. Crockett, Ed. Belmont, CA: Duxbury, 2006, ch. 12, pp. 545–583.

- [4] A. T. Arnholt and B. Evans, “Package ‘BSDA’,” 2017. [Online]. Available: <https://cran.r-project.org/web/packages/BSDA/BSDA.pdf>
- [5] C. Jennett, A. L. Cox, P. Cairns, S. Dhoparee, A. Epps, T. Tijs, and A. Walton, “Measuring and Defining the Experience of Immersion in Games,” *International Journal of Human-Computer Studies*, vol. 66, no. 9, pp. 641–661, sep 2008. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S1071581908000499>
- [6] J. J. Laviola Jr., “A Discussion of Cybersickness in Virtual Environments,” vol. 32, no. 1, pp. 47 – 56, Jan 2000. [Online]. Available: <https://dl.acm.org/citation.cfm?id=333344>
- [7] S. Davis, K. Nesbitt, and E. Nalivaiko, “A Systematic Review of Cybersickness,” in *Proceedings 2014 Conference on Interactive Entertainment*, K. Blackmore, K. Nesbitt, and S. P. Smith, Eds. Newcastle, NSW, Australia: ACM Press, 2014, pp. 1–9. [Online]. Available: <https://dl.acm.org/citation.cfm?doid=2677758.2677780>

CHAPTER 6

Conclusion

This thesis presented the design of an experiment and construction of a system aimed at answering whether vibrotactile feedback will increase an exergame user's intrinsic motivation to play the exergame or their immersion within the exergame. The exergame used in the experiment was built in-house, alongside the system used to play it. The experiment consisted of two conditions: (1) the exergame with vibrotactile feedback and (2) the exergame without vibrotactile feedback. For both experiment conditions the same exergame was used. To test the system and evaluate the hypothesis, a user study was conducted. The data produced by the experiment was presented in Chapter 5 alongside an analysis of the data collected from the user study. Both the results of the data produced by the system and responses to my questionnaires indicate that the system and exergame function as intended.

The study consisted of five men and two women for a total of seven participants. Most participants had little experience with virtual reality and a varying amount of experience with video games. Most participants did not bike on a regular basis, although the majority did aerobic exercises at least once a week. The study examined the level of intrinsic motivation, immersion, and heart rate between the two experimental conditions. Intrinsic motivation was measured through the interest/enjoyment subscale of the Intrinsic Motivation Inventory. To measure immersion I developed a shorter questionnaire based off of the one presented in [1]. Finally, heart rate was measured through a Polar OH1 heart rate monitor.

An analysis of the intrinsic motivation and immersion questionnaire produced mixed results. The results of the Sign test ($p = 0.0625$) and Wilcoxon signed-rank

test ($p = 0.02344$) on the data collected from the intrinsic motivation questionnaire showed a significant difference between the regular and vibrotactile exergame at a significance level of $\alpha = 0.1$. These results support for my hypothesis that vibrotactile feedback can increase intrinsic motivation in exergames. Unfortunately with the analysis of the immersion questionnaire, neither the Sign test ($p = 0.5$) nor Wilcoxon signed-rank test ($p = 0.5$) provided evidence to support my second hypothesis that vibrotactile feedback can increase immersion in an exergame. Finally due to time constraints, the analysis of the heart rate data collected during the study could not be included.

The post-experiment questionnaire showed many participants thought they would use an exercise bike similar to the system longer and more often. However, most did not think they would prefer to use a similar system for regular exercise. Most participants felt that the virtual bicycle used in the exergame behaved similarly to a real bicycle. I believe this is an indicator that the model is implemented correctly and the sensors are providing accurate data. A majority of participants reported one or more symptoms of cybersickness, an illness similar to motion sickness.

6.1 Future Work

I would like to present some avenues for future work related to the system and additional directions for research. The list below, in no particular order, is based on feedback and observations from both participants in the user study and testing the system myself.

- **Larger Sample Size and Shorter Experiment Time:** A primary direction for any related future work should be to carry out this study on a larger sample of the population with a wider age range. As it stands the results from the study presented here are promising, particularly with regards to in-

trinsic motivation. One major drawback is the small amount of participants in the study. I attribute this partially to the length of an experiment session, which is 40 to 45 minutes. I believe that a shorter experiment session, somewhere between 15 to 20 minutes, would be more appealing to subjects in the population of interest.

- **Revise the immersion questionnaire:** As noted in Chapter 5 the immersion questionnaire used had a low internal consistency. An improvement to the study, in addition to the above, would be to develop an immersion questionnaire with a higher internal consistency than the current one. Additionally since the measure for immersion in this study was based solely on the immersion questionnaire low internal consistency could be a reason why no significant results were found.
- **Constant “Vibration Textures”:** One of the free-form comments left by a participant was: *“Maybe having a more consistent amount of vibration for road texture as well as running over the manhole covers would add to realism.”* This could be an interesting direction to explore with the system built here, given the recommendation by Alizadeh et al. that vibrotactile feedback should not last longer than five seconds [2]. A starting point could be a recently published paper by Rakhmatov et al., who looked at applying recorded surface vibrations to vibration on a virtual bicycle [3].
- **Make High-Speed Turns Harder:** Unlike a real bicycle, the system currently allow a user to quickly make turns regardless of the current speed. An improvement to the system as a bicycle simulator would be to add a steering “dead-zone” so that as a user pedals faster on the bicycle it becomes harder to make sharp turns. One way to do this would be to attach a linear actua-

tor, a type of motor which moves in a line, to the front wheel via a rope and use the actuator to tighten the rope as the speed of the bicycle increase.

- **Software Package:** I am currently developing a package for the Serial Port Interface and Bicycle Controller to allow other researchers to adopt the system for use in their own projects.

List of References

- [1] C. Jennett, A. L. Cox, P. Cairns, S. Dhoparee, A. Epps, T. Tijs, and A. Walton, “Measuring and Defining the Experience of Immersion in Games,” *International Journal of Human-Computer Studies*, vol. 66, no. 9, pp. 641–661, sep 2008. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S1071581908000499>
- [2] H. Alizadeh, R. Tang, E. Sharlin, and A. Tang, “Haptics in Remote Collaborative Exercise Systems for Seniors,” in *Proceedings Extended Abstracts on Human Factors in Computing Systems*. Toronto, ON, Canada: ACM Press, 2014, pp. 2401–2406. [Online]. Available: <http://dx.doi.org/10.1145/2559206.258131>
- [3] R. Rakhmatov, A. Abdulali, W. Hassan, M. Kim, and S. Jeon, “Virtual Reality Bicycle with Data-Driven Vibrotactile Responses from Road Surface Textures,” in *Proceedings 2018 IEEE Games, Entertainment, Media Conference, GEM 2018*. Galway, Ireland: IEEE, 2018, pp. 496–500.

APPENDIX A

Experiment Questionnaires

A.1 Pre-Experiment Questionnaire

What is your age?

Slider response between 18 and 65

What is your gender?

-Male

-Female

How much experience do you have with virtual reality?

- visual analog scale

How much experience do you have with video games?

- visual analog scale

What genre of games do typically prefer to play

(Choose all that apply)

-Action

-Adventure

-Role-playing

-Simulation

-Strategy

-Sports

-MMO

-Other

How often, on average, do you perform aerobic exercises, such as running or biking?

- Less than once a month

- Once a month

- A few times a month

- About once a week

- A few times a week

- Every day

Over the course of a month, how often do you ride a bicycle?

- Less than once a month

- Once a month

- A few times a month

- About once a week
- A few times a week
- Every day

A.2 Intrinsic Motivation Inventory - Interest/Enjoyment subscale

All questions are answered on a visual analog scale.

I enjoyed playing the {exergame/haptic exergame} very much.

Strongly Disagree _____ Strongly Agree

The {exergame/haptic exergame} was fun to play.

Strongly Disagree _____ Strongly Agree

(Reverse)

I thought the {exergame/haptic exergame} was boring.

Strongly Disagree _____ Strongly Agree

(Reverse)

The {exergame/haptic exergame} did not hold my attention at all.

Strongly Disagree _____ Strongly Agree

I would describe the {exergame/haptic exergame} as very interesting.

Strongly Disagree _____ Strongly Agree

I thought the {exergame/haptic exergame} was quite enjoyable.

Strongly Disagree _____ Strongly Agree

While I was playing the {exergame/haptic exergame}, I was thinking about how much I enjoyed it.

Strongly Disagree _____ Strongly Agree

A.3 Immersion Questionnaire

All questions are on a visual analog scale.

How engaged did you feel while playing the game?

I was not engaged at all.

I was engaged a great deal.

How surprised were you when the game informed you three minutes had passed?

I was not surprised at all.

I was surprised a great deal.

How much do you feel you would like to continue playing the game?

I would not like to continue playing at all.

I would like to continue playing a great deal.

Did you feel that the collectibles added to your engagement while playing the game?

I do not feel that the collectibles added to my engagement at all.

I feel that the collectibles added to my engagement a great deal.

How much did you feel you were aware of the real world around you while playing the game?

I was extremely aware of the real world around me.

I was not extremely aware of the real world at all.

(Reverse)

How immersed did you feel in the game while playing it?

I felt very immersed in the game.

I did not feel I was very immersed in the game.

A.4 Post-Experiment Questionnaire

Using the exergame with haptic feedback would cause me to use an exercise bike more often.

- Definitely would
- Probably would
- Neutral
- Definitely would not
- Probably would not

Using the exergame with haptic feedback would cause me to use an exercise bike for longer.

- Very unlikely
- Unlikely
- Neither likely or unlikely
- Likely
- Very likely

Did you feel that the virtual bicycle behaved the same as a real bicycle?

- 7-point Likert item (Strongly Disagree - Strongly Agree)

Did you experience any of the following?

- Light headedness
- Disorientation
- Nausea
- Other (Free-form text)

Would you prefer to use an exergame with haptic feedback like the one presented in the study for regular exercise?

- Definitely would
- Probably would
- Neutral
- Definitely would not
- Probably would not

Are there any comments you would like to make regarding either version of the game?

- Text box

A.5 Physical Activity Readiness Questionnaire



Pass / Fail

Data Collection Sheet

NAME: _____ DATE: _____

HEIGHT: _____ in. WEIGHT: _____ lbs. AGE: _____

PHYSICAL ACTIVITY READINESS QUESTIONNAIRE (PAR-Q)

| | Questions | Yes | No |
|---|---|-----|----|
| 1 | Has your doctor ever said that you have a heart condition and that you should only perform physical activity recommended by a doctor? | | |
| 2 | Do you feel pain in your chest when you perform physical activity? | | |
| 3 | In the past month, have you had chest pain when you were not performing any physical activity? | | |
| 4 | Do you lose your balance because of dizziness or do you ever lose consciousness? | | |
| 5 | Do you have a bone or joint problem that could be made worse by a change in your physical activity? | | |
| 6 | Is your doctor currently prescribing any medication for your blood pressure or for a heart condition? | | |
| 7 | Do you know of <u>any</u> other reason why you should not engage in physical activity? | | |

If you have answered "Yes" to one or more of the above questions, consult your physician before engaging in physical activity. Tell your physician which questions you answered "Yes" to. After a medical evaluation, seek advice from your physician on what type of activity is suitable for your current condition.

If you have answered "Yes" to one or more of the above questions, you are ineligible to participate in this study. Thank you for your interest in this study and for your participation today.

If you have answered "No" to all of the above questions the investigators will now check your blood pressure and measure your pulse.

Record subject measurements here:

Measured Blood Pressure: _____ / _____ mmHg Measured Pulse: _____ bpm

Investigators: _____

Blood pressure should be measured three times and the results averaged. A blood pressure not greater than 120 mmHg systolic and 80 mmHg diastolic is considered eligible for participation. A pulse measured between 60 and 100 bpm will be considered eligible for participation in the study.

APPENDIX B

Glossary

Virtual Environment (VE) A three dimensional scene which is displayed to the user through a monitor/television screen, projector, head-mounted display, or other electronic means.

Virtual Reality (VR) From *The VR Book*: “a computer-generated digital environment that can be experienced and interacted with as if that environment were real.”

Video Game A type of computer program which displays a two or three dimensional scene which the user interacts with and controls.

Head-Mounted Display (HMD) Also abbreviated HMD, this is a hardware device which is worn on the user’s head. It typically consists of two screens, one for each eye, and displays a virtual environment which the user may interact with. The perspective of the scene displayed will change depending on the orientation of the user’s head.

Exergame Shorthand for exercise game, a type of video game which incorporates some form of physical activity into the game controls.

Self-Determination Theory (SDT) A theory of motivation within psychology which deals with understanding how social environments and contexts affect human motivation.

Intrinsic Motivation Within Self-Determination Theory this is the most autonomous type of motivation. These are actions which are done for the pure enjoyment of the action.

Presence A psychological state which is, in the context of a virtual environment, commonly referred to as the feeling of “being there.”

Flow A mental state where a person has complete immersion in a task to the point where they lose their sense of self but retain a deep sense of control.

BIBLIOGRAPHY

- 3D Systems, “The Touch Haptic Device,” Accessed: 2019-02-18. [Online]. Available: <https://www.3dsystems.com/haptics-devices/touch>
- 3D Systems, “Haptic Devices: Add the Sense of Touch to Your Digital World,” Tech. Rep., 2018. [Online]. Available: https://www.3dsystems.com/sites/default/files/2018-08/3d-systems-haptic-device-en-web-2018-08-03_0.pdf
- Alizadeh, H., Tang, R., Sharlin, E., and Tang, A., “Haptics in Remote Collaborative Exercise Systems for Seniors,” in *Proceedings Extended Abstracts on Human Factors in Computing Systems*. Toronto, ON, Canada: ACM Press, 2014, pp. 2401–2406. [Online]. Available: <http://dx.doi.org/10.1145/2559206.258131>
- American Heart Association, “All About Heart Rate (Pulse),” Accessed: 2018-09-17. [Online]. Available: <http://www.heart.org/en/health-topics/high-blood-pressure/the-facts-about-high-blood-pressure/all-about-heart-rate-pulse>
- Arduino, “Analogwrite,” 2019, Accessed: 2019-03-19. [Online]. Available: <https://www.arduino.cc/reference/en/language/functions/analog-io/analogwrite/>
- Arnholt, A. T. and Evans, B., “Package ‘BSDA’,” 2017. [Online]. Available: <https://cran.r-project.org/web/packages/BSDA/BSDA.pdf>
- Barathi, S. C., O’Neill, E., Lutteroth, C., Finnegan, D. J., Farrow, M., Whaley, A., Heath, P., Buckley, J., Dowrick, P. W., Wuensche, B. C., and Bilzon, J. L. J., “Interactive Feedforward for Improving Performance and Maintaining Intrinsic Motivation in VR Exergaming,” in *Proceedings 2018 CHI Conference on Human Factors in Computing Systems - CHI ’18*. Montreal QC, Canada: ACM Press, 2018. [Online]. Available: <http://dl.acm.org/citation.cfm?doid=3173574.3173982>
- Bogost, I., “The Rhetoric of Exergaming,” Georgia Institute of Technology, Atlanta, GA, Tech. Rep., 2005. [Online]. Available: http://bogost.com/writing/the_rhetoric_of_exergaming/
- Bolton, J., Lirette, D., Lambert, M., and Unsworth, B., “PaperDude : A Virtual Reality Cycling Exergame,” in *Proceedings Extended Abstracts on Human Factors in Computing Systems*. Toronto, ON, Canada: ACM Press, 2014, pp. 475–478.

- Booth, F. W., Roberts, C. K., and Laye, M. J., "Lack of Exercise Is a Major Cause of Chronic Diseases," *Comprehensive Physiology*, vol. 2, no. 2, pp. 1143–1211, apr 2012. [Online]. Available: <http://doi.wiley.com/10.1002/cphy.c110025>
- Boulanger, P., Pournajib, A., Mott, W., and Schaeffer, S., "A Low-Cost Virtual Reality Bike for Remote Cardiac Rehabilitation," in *Proceedings EuroVR*, Laval, France, 2017, pp. 155–166. [Online]. Available: http://link.springer.com/10.1007/978-3-319-72323-5_10
- Brown, E. and Cairns, P., "A Grounded Investigation of Game Immersion," in *Proceedings Extended Abstracts of the 2004 Conference on Human Factors and Computing Systems*. Vienna, Austria: ACM Press, 2004, pp. 1297–1300.
- Carraro, G. U., Cortes, M., Edmark, J. T., and Ensor, J. R., "The Peloton Bicycling Simulator," in *Proceedings Third Symposium on Virtual Reality Modeling Language*. Monterey, CA, USA: ACM Press, 1998, pp. 63–70. [Online]. Available: <http://portal.acm.org/citation.cfm?doid=271897.274372>
- Centers for Disease Control and Prevention, "High Blood Pressure Fact Sheet," 2016, Accessed: 2017-12-17. [Online]. Available: https://www.cdc.gov/dhdsp/data_statistics/fact_sheets/fs_bloodpressure.htm
- Centers for Disease Control and Prevention, "Measuring Blood Pressure," 2018, Accessed: 2019-01-08. [Online]. Available: <https://www.cdc.gov/bloodpressure/measure.htm>
- Csikszentmihalyi, M., *Beyond Boredom and Anxiety: Experiencing Flow in Work and Play*. San Fransisco, CA, USA: Jossey-Bass Publishers, 1975.
- D'Agostino Sr., R. B., Sullivan, L. M., and Beiser, A. S., "Nonparametric Tests," in *Introductory Applied Biostatistics*, 1st ed., Crockett, C., Ed. Belmont, CA: Duxbury, 2006, ch. 12, pp. 545–583.
- Davis, S., Nesbitt, K., and Nalivaiko, E., "A Systematic Review of Cybersickness," in *Proceedings 2014 Conference on Interactive Entertainment*, Blackmore, K., Nesbitt, K., and Smith, S. P., Eds. Newcastle, NSW, Australia: ACM Press, 2014, pp. 1–9. [Online]. Available: <https://dl.acm.org/citation.cfm?doid=2677758.2677780>
- DeVellis, R. F., "Reliability," in *Scale Development*, 2nd ed. London: SAGE Publications, 2003, ch. 3, pp. 27–47.
- Ebben, W. and Brudzynski, L., "Motivations and Barriers to Exercise Among College Students," *Journal of Exercise Physiologyonline (JEPonline)*, vol. 11, no. 5, pp. 1–11, 2008.

- El Saddik, A., Orozco, M., Eid, M., and Cha, J., *Haptics Technologies*, 1st ed., ser. Springer Series on Touch and Haptic Systems. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011.
- Engeser, S., Ganesh, M. S., Moneta, G. B., Pfeifer, C., and Peifer, C., “Advances in Flow Research,” in *Advances in Flow Research*, Engeser, S., Ed. New York, NY: Springer New York, 2012, ch. 1, p. 231. [Online]. Available: <http://www.springerlink.com/index/10.1007/978-1-4614-2359-1>
<http://link.springer.com/10.1007/978-1-4614-2359-1>
<http://link.springer.com/10.1007/978-1-4614-2359-1>
- Guthold, R., Stevens, G. A., Riley, L. M., and Bull, F. C., “Worldwide Trends in Insufficient Physical Activity From 2001 to 2016: A Pooled Analysis of 358 Population-Based Surveys with 1.9 Million Participants,” *The Lancet Global Health*, vol. 6, no. 10, pp. e1077–e1086, 2018. [Online]. Available: <https://linkinghub.elsevier.com/retrieve/pii/S2214109X18303577>
- Herpers, R., Heiden, W., Kutz, M., Scherfgen, D., Hartmann, U., Bongartz, J., and Schulzyk, O., “FIVIS Bicycle Simulator,” in *Proceedings 2008 Conference on Future Play Research, Play, Share - Future Play '08*. Toronto, Ontario, Canada: ACM Press, 2008, pp. 244–247. [Online]. Available: <http://portal.acm.org/citation.cfm?doid=1496984.1497035>
- Hossain, M. S., Hassan, M. M., and Alamri, A., “An Exergame Framework for Obesity Monitoring and Management,” in *Proceedings HAVE 2013 - 2013 IEEE International Symposium on Haptic Audio-Visual Environments and Games*, Istanbul, Turkey, 2013.
- Hung, K., Wan, N., Choy, S. O., Chu, C., and Chow, D. H., “Design of an Exergaming System with Haptic Feedback for the Investigation of Energy Expenditure and Muscle Activities,” in *IEEE International Conference on Industrial Informatics (INDIN)*, Emden, Germany, 2017, pp. 886–889.
- Interactive Fitness, “Expresso Bikes,” Accessed: 2018-11-06. [Online]. Available: <https://expresso.com/Home>
- International Society for Presence Research, “The Concept of Presence: Explication Statement,” 2000, Accessed: 2019-02-18. [Online]. Available: <https://ispr.info/about-presence-2/about-presence/>
- Jackson, S. A., “Flow,” in *The Oxford Handbook of Human Motivation*, 1st ed., Nathan, P. E. and Ryan, R. M., Eds. New York, NY, U.S.A.: Oxford University Press, Inc., 2012, ch. 8, pp. 127–140.
- Jennett, C., Cox, A. L., Cairns, P., Dhoparee, S., Epps, A., Tijs, T., and Walton, A., “Measuring and Defining the Experience of Immersion in Games,” *International Journal of Human-Computer Studies*,

- vol. 66, no. 9, pp. 641–661, sep 2008. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S1071581908000499>
- JORDANDEE, “Pulse Width Modulation,” Accessed: 2019-03-19. [Online]. Available: <https://learn.sparkfun.com/tutorials/pulse-width-modulation/all>
- Kwon, D.-S., Yang, G.-H., Lee, C.-W., Shin, J.-C., Park, Y., Jung, B., Lee, D. Y., Lee, K., Han, S.-H., Yoo, B.-H., Wohn, K.-Y., and Ahn, J.-H., “KAIST Interactive Bicycle Simulator,” in *Proceedings 2001 ICRA. IEEE International Conference on Robotics and Automation*, vol. 3. Seoul, South Korea: IEEE, 2001, pp. 2313–2318. [Online]. Available: <http://ieeexplore.ieee.org/document/932967/>
- Laviola Jr., J. J., “A Discussion of Cybersickness in Virtual Environments,” vol. 32, no. 1, pp. 47 – 56, Jan 2000. [Online]. Available: <https://dl.acm.org/citation.cfm?id=333344>
- Lee, S., Kim, W., Park, T., and Peng, W., “The Psychological Effects of Playing Exergames: A Systematic Review,” *Cyberpsychology, Behavior, and Social Networking*, vol. 20, no. 9, sep 2017. [Online]. Available: <http://online.liebertpub.com/doi/10.1089/cyber.2017.0183>
- Löchtefeld, M., Krüger, A., and Gellersen, H., “DeceptiBike: Assessing the Perception of Speed Deception in a Virtual Reality Training Bike System,” in *Proceedings 9th Nordic Conference on Human-Computer Interaction - NordiCHI '16*. New York, New York, USA: ACM Press, 2016, pp. 1–10. [Online]. Available: <http://dl.acm.org/citation.cfm?doid=2971485.2971513>
- Lombard, M. and Ditton, T., “At the Heart of It All: The Concept of Presence,” *Journal of Computer-Mediated Communication*, vol. 3, no. 2, pp. 0–0, jun 2006. [Online]. Available: <https://academic.oup.com/jcmc/article/4080403>
- Morelli, T., Foley, J., and Folmer, E., “VI-Bowling: A Tactile Spatial Exergame for Individuals with Visual Impairments,” in *Proceedings 12th International ACM SIGACCESS Conference on Computers and Accessibility*. Orlando, Florida, USA: ACM Press, 2010, pp. 179–186. [Online]. Available: <https://dl.acm.org/citation.cfm?id=1878836>
- Morelli, T., Foley, J., Lieberman, L., and Folmer, E., “Pet-N-Punch: Upper Body Tactile/Audio Exergame to Engage Children with Visual Impairments into Physical Activity,” in *Proceedings Graphics Interface Conference*. St. John’s, Newfoundland, Canada: Canadian Human-Computer Communications Society School of Computer Science, 2011, pp. 223–230.
- Morelli, T. and Folmer, E., “Real-time Sensory Substitution to Enable Players Who are Blind to Play Video Games Using Whole Body Gestures,” *Entertainment Computing*, vol. 5, no. 1, pp. 83–90, 2014.

- Nunes, M., Nedel, L., and Roesler, V., “Motivating People to Perform Better in Exergames: Competition in Virtual Environments,” in *Proceedings 29th Annual ACM Symposium on Applied Computing - SAC '14*. Gyeongju, Republic of Korea: ACM Press, 2014, pp. 970–975. [Online]. Available: <http://dl.acm.org/citation.cfm?doid=2554850.2555009>
- Orland, K. and Remo, C., “Games For Health: Noah Falstein On Exergaming History,” 2008, Accessed: 2018-10-27. [Online]. Available: http://www.gamasutra.com/view/news/109512/Games_For_Health_Noah_Falstein_On_Exergaming_History.php
- Precision Microdrives, “AB-003 : Driving Linear Resonance Vibration Actuators,” Accessed: 2019-02-18. [Online]. Available: <https://www.precisionmicrodrives.com/content/ab-003-driving-linear-resonance-vibration-actuators/>
- Precision Microdrives, “Eccentric Rotating Mass Vibration Motors - ERMs,” Accessed: 2019-02-16. [Online]. Available: <https://www.precisionmicrodrives.com/vibration-motors/eccentric-rotating-mass-vibration-motors-erms/>
- Precision Microdrives, “Integration Guide: Haptic Feedback and Vibration Alerting for Handheld Products,” pp. 1–20, Accessed: 2019-03-18. [Online]. Available: https://www.precisionmicrodrives.com/wp-content/uploads/2016/01/haptic-feedback-vibration-alerting-for-handheld-products_0.pdf
- Precision Microdrives, “Vibration Motors,” Accessed: 2019-02-16. [Online]. Available: <https://www.precisionmicrodrives.com/vibration-motors/>
- Rakhmatov, R., Abdulali, A., Hassan, W., Kim, M., and Jeon, S., “Virtual Reality Bicycle with Data-Driven Vibrotactile Responses from Road Surface Textures,” in *Proceedings 2018 IEEE Games, Entertainment, Media Conference, GEM 2018*. Galway, Ireland: IEEE, 2018, pp. 496–500.
- Ramsamy, P., Haffegge, A., Jamieson, R., and Alexandrov, V., “Using Haptics to Improve Immersion in Virtual Environments,” in *Proceedings Computational Science*. Reading, UK: Springer, Berlin, Heidelberg, 2006, pp. 603–609.
- Ranky, R., Sivak, M., Lewis, J., Gade, V., Deutsch, J. E., and Mavroidis, C., “VRACK - Virtual Reality Augmented Cycling Kit: Design and Validation,” in *Proceedings 2010 IEEE Virtual Reality Conference (VR)*. Waltham, MA, USA: IEEE, mar 2010, pp. 135–138. [Online]. Available: <http://ieeexplore.ieee.org/document/5444798/>
- Ryan, R. M. and Deci, E. L., *Self-Determination Theory: Basic Psychological Needs in Motivation, Development, and Wellness*, 1st ed. New York, NY, USA: The Guilford Press, 2017.

- Shaw, L. A., Wuensche, B. C., Lutteroth, C., Buckley, J., and Corballis, P., “Evaluating Sensory Feedback for Immersion in Exergames,” in *Proceedings Australasian Computer Science Week Multiconference on - ACSW '17*. Geelong, Australia: ACM Press, 2017. [Online]. Available: <http://dl.acm.org/citation.cfm?doid=3014812.3014823>
- Shaw, L. A., Wunsche, B. C., Lutteroth, C., Marks, S., Buckley, J., and Corballis, P., “Development and Evaluation of an Exercycle Game Using Immersive Technologies,” in *Proceedings 8th Australasian Workshop on Health Informatics and Knowledge Management (HIKM 2015)*, Maeder, A. and Warren, J., Eds., vol. 164, no. January. Parramatta, Australia: CRPIT, 2015, pp. 27–30. [Online]. Available: <https://www.cs.auckland.ac.nz/~lutteroth/publications/ShawEtAl2015-ImmersiveExercycle.pdf>
- Skarbez, R., Brooks, Jr., F. P., and Whitton, M. C., “A Survey of Presence and Related Concepts,” *ACM Computing Surveys*, vol. 50, no. 6, pp. 1–39, 2017.
- Slater, M. and Wilbur, S., “A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments,” *Presence*, vol. 6, no. 6, pp. 603–616, 1997. [Online]. Available: <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.472.622&rep=rep1&type=pdf>
- Stach, T. and Graham, T. C. N., “Exploring Haptic Feedback in Exergames,” in *Proceedings INTERACT 2011*, Campos, P., Graham, N., Jorge, J., Nunes, N., Palanque, P., and Winckler, M., Eds., vol. 6947. Springer, Berlin, Heidelberg, 2011, pp. 18–35. [Online]. Available: http://link.springer.com/10.1007/978-3-642-23771-3_2
- std: Self-Determination Theory, “Intrinsic Motivation Inventory (IMI) Scale,” Accessed: 2018-09-14. [Online]. Available: <http://selfdeterminationtheory.org/intrinsic-motivation-inventory/>
- Tang, Y.-M., Tsoi, M. H.-C., Fong, D. T.-P., Lui, P. P.-Y., Hui, K.-C., and Chan, K.-M., “The Development of a Virtual Cycling Simulator,” in *Proceedings Second International Conference on Edutainment*. Hong Kong, China: Springer, Berlin, Heidelberg, 2007, pp. 162–170. [Online]. Available: https://doi.org/10.1007/978-3-540-73011-8_18
https://doi.org/10.1007/978-3-540-73011-8_18
- University of Rhode Island Office of Research Integrity, “Exercise Policy,” Kingston, RI, pp. 1–2. [Online]. Available: <https://www.irbnet.org/release/export/download.jsp?libId=21947>
- U.S. Department of Health and Human Services, “2008 Physical Activity Guidelines for Americans,” Tech. Rep., 2008. [Online]. Available: https://health.gov/paguidelines/second-edition/report/pdf/PAG_Advisory_Committee_Report.pdf

- Weiss, M. R. and Amorose, A. J., “Motivational Orientation and Sport Behavior,” in *Advances in Sport Psychology*, 3rd ed., Horn, T. S., Ed. Champaign, IL: Human Kinetics, 2008, p. 133.
- Witmer, B. and Singer, M., “Measuring Presence in Virtual Environments: A Presence Questionnaire,” *Presence*, vol. 7, no. 3, pp. 225–240, 1998.